Specific property analysis of thin-film, semiconductors for effective optical logical operations

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Specific property analysis of thin-film semiconductors for effective
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In this thesis, a straightforward laser modulation concept is discussed which has the potential to be employed in similar ways as microelectromechanical systems (MEMS) in optical switching. The concept is realized by crossing two laser lines in a semiconducting thin-film on a glass or flexible polymer substrate, i.e., by switching one of the beams, one achieves a clearly resolved (up to 30%) modulation of the other beam. In case of thin-film GaAs, response times in the picosecond range are possible, whereas ZnTe and CdS exhibits relatively slow but more resolved modulation. Both the transmission and reflection modes of the modulation under different conditions such as various intensities and laser energies were investigated. The experiments were carried out in steady state with continuous wave lasers and time resolved mode with short laser pulses in the order
of nanoseconds. Furthermore, electro-optic hybridization possibilities of the modulation concept were also investigated, utilizing thin-film semiconductor as an active optical element. All the experiments have been carried out at ambient conditions with moderate laser powers on the order of 10 mW. Additional experiments were carried out with the intention to relate the concept to photo induced reversible macroscopic property changes in the material such as reflection coefficient and refractive index variations. Reflection spectra of the materials were measured with and without the influence of additional laser illumination. A clear reflectance change was observed in all of the material with a pronounced difference near its band gap.
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## Table of Contents

Acknowledgments ................................................................................................................................ iv  
List of Figures ...................................................................................................................................... viii  
Introduction and Theoretical Considerations ................................................................................... 1  
  1.1 Introduction ................................................................................................................................ 1  
  1.2 Theoretical Consideration ............................................................................................................. 4  
    1.2.1 Transmission of light in an absorbing medium ......................................................................... 4  
    1.2.2 Fabry-Perot Etalon .................................................................................................................. 9  
Experimental Setups .......................................................................................................................... 16  
  2.1 Introduction ................................................................................................................................ 16  
  2.2 Optical switch realized with cw laser sources ............................................................................. 17  
  2.3 Nanosecond pulsed switch .......................................................................................................... 18  
  2.4 Reflection and transmission measurements .............................................................................. 20  
  2.5 Reflection under laser illumination .............................................................................................. 21  
  2.6 Sample preparation- Pulsed Laser Deposition (PLD) .................................................................. 22  
Optical Switching ................................................................................................................................ 23  
  3.1 Introduction ................................................................................................................................ 23  
  3.2 The Original telephone network ................................................................................................ 24  
  3.3 Multiplexing ................................................................................................................................ 25  
    3.3.1 Frequency Division Multiplexing .............................................................................................. 26  
    3.3.2 Time Division Multiplexing ...................................................................................................... 27
3.4 Optical Networks and optical Switching ......................................................... 28

3.5 Optical switch ............................................................................................. 29

3.6 Optical Switching Technologies ................................................................... 30

Photonic Digitizing............................................................................................. 32

4.1 Making the Case for All-optical Switching ................................................. 32

4.2 Laser modulation ......................................................................................... 34

4.2.1 Results for CdS with cw lasers ................................................................. 37

4.2.2 Results for ZnTe on glass ...................................................................... 39

4.2.3 Results for GaAs on glass ..................................................................... 43

4.3 Rationalization of the cw laser modulation ............................................... 45

4.4 Switch Characteristics.................................................................................. 48

4.3.1 Intensity Dependence ............................................................................. 48

4.3.2 Wavelength dependence ....................................................................... 52

4.3.3 Opto-electric hybrid switch .................................................................. 54

4.5 Pulsed Laser Modulation ............................................................................ 57

4.6 Reflection pattern variations ...................................................................... 61

Reflection Coefficient Measurements............................................................... 66

5.1 Transmittance and Reflectance of a thin film ............................................. 66

5.2 Reflection coefficient of CdS ..................................................................... 68

5.3 Laser bleaching of the reflectance of ZnTe, GaAs and CdS ...................... 71

Conclusions and Future Work ......................................................................... 76

6.1 Conclusions ................................................................................................. 76
6.2 Summary of results ........................................................................................................... 77
6.2 Applications and future work .......................................................................................... 78
APPENDIX A .................................................................................................................. 80
Bibliography .................................................................................................................. 83
References ....................................................................................................................... 84
List of Figures

1.1 Reflection and refraction of light from an interface 7
1.2 Multiple reflections from a thin film 9
1.3 Reflection and refraction from a single film on a substrate 11
2.1 Experimental setup for the steady state optical switch 17
2.2 Experimental setup for the pulsed switch 18
2.3 Experimental setup for reflection and transmission measurements 20
2.4 Experimental setup for laser bleaching of monochromatic light 21
2.5 General scheme of a PLD setup 22
3.1 Introduction of switching in telephone networks 24
3.2 Evolution of the mechanical switch into a digital electronic switch 26
3.3 Time Division Multiplexing 27
4.1 Beam paths for the reflection switch arrangement 34
4.2 Beam paths for the transmission switch arrangement 35
4.3 Reflection and transmission modulations from film surface on CdS/plastic sample with cw laser 37
4.4 Reflection and transmission modulations from film/glass interface on CdS/glass sample with cw laser 38
4.5 Normalized reflection and transmission for ZnTe/glass from film surface 39
4.6 Normalized reflection and transmission for ZnTe/glass from film – glass interface 40
4.7 Normalized reflection and transmission for ZnTe/ITO on the film surface 41
4.8 Normalized reflection and transmission for ZnTe/ITO on the film – ITO interface

4.9 Normalized reflection and transmission switch for GaAs/glass from the film surface

4.10 Normalized reflection and transmission switch for GaAs/glass from the glass-film interface

4.11 Dependence of the green transmission (probe beam) on green and red (control beam) intensity

4.12 Dependence of the red transmission (probe beam) on green (control beam) and red intensity

4.13 Reflection modulations at various incident powers of control beam

4.14 Transmission modulations at various incident powers of control beam

4.15 Reflection and transmission modulation versus photon energy from (a) the film surface (b) film-glass interface

4.16 Wavelength versus transmission modulation amplitude for ZnTe on ITO a) Film surface b) ZnTe/Glass interface

4.17 Schematic for the hybrid operation

4.18 Modulation amplitude versus applied electric field of the sample

4.10 Modulation amplitude a) Reflection, b) Transmission versus applied electric field of the sample, film surface

4.20 Temporally resolved real time reflection digitizing from CdS

4.21 Recovery time of the CdS switch

4.22 Temporally resolved real time reflection digitizing from GaAs.
Red laser modulated with a 6ns pulses from a Nd:YAG laser

4.23 Recovery time of the GaAs switch  

4.24 Comparison of the reflection modulation for CdS and GaAs on plastic  

4.25 (a) The intrinsic reflected red laser spot from CdS film  

surface with no additional green laser irradiation  

4.25 (b) The intrinsic reflected red laser spot from GaAs film surface  

with additional green laser irradiation  

4.26 (a) The intrinsic reflected red laser spot from GaAs film surface  

with no additional green laser irradiation, i.e., control beam off  

4.26 (b) The intrinsic reflected red laser spot from GaAs film surface  

with additional green laser irradiation, i.e., control beam on  

4.27 (a) Atomic Force Microscopy surface image of CdS  

4.27 (b) Atomic Force Microscopy surface image of GaAs  

5.1 Multiple internal reflections of a thin solid film with thickness d  

and absorption coefficient $\alpha$  

5.2 Wave length dependence of the reflected and transmitted  

intensities from the CdS thin film  

5.3 Change of reflectance, transmittance and absorption of thin-film  

CdS with incident wavelength  

5.4 Reflection coefficient versus wavelength of incident light  

5.5 Change in reflectance due to additional laser irradiation  

5.6 Reflectance vs. incident wavelength for ZnTe on plastic  

5.7 Reflectance vs. incident wavelength for GaAs on plastic  

x
5.8 Reflectance versus incident wavelength for CdS on plastic
6.1 employing laser crossing to realize logic NOR operation
6.2 Logic NOR realization using laser modulation
Chapter One

Introduction and Theoretical Considerations

1.1 Introduction

The realization of a single mode fiber with attenuation below 20 decibels at 632.8 nm in year 1970 at Corning Glass Works started the dramatic technological development of optical data transmission.\textsuperscript{1} As a consequence, during the late 1970s and 1980s, the growing impact of fibers on global data transfer provoked notable research efforts on the replacement of electronic logics with optically operated switching techniques.\textsuperscript{2-4} Concepts and technologies for optical computing were stubbornly pursued by many research groups worldwide but were finally abandoned in the early 1990s due to several reasons.\textsuperscript{5} Probably the most important reasons might have been the relatively high power consumption for optical switching and the fact that the achieved optical methods did not or hardly exceeded electronics at that time.

Meanwhile, due to the unmatched fiber transmission speed (exceeding terabit per second), which bypasses the limitation of electric connections, optically driven logic operations regained considerable interest during the last years.\textsuperscript{6} However, in contrast to the optical switching approach of the past, i.e., to surpass in particular the
speed of electronic operations, solutions, which maintain inherent conceptional advantages of optical devices, appear to be technologically acceptable. Such devices are mirror-based microelectromechanical systems (MEMS).\textsuperscript{1,6-8} The MEMS has proven to be commercially successful but the drawback is the requirement of an adjunct electric power supply in order to drive the gimbaled mirror arrays. The alternative would be to initiate logic operations exclusively with photons, resulting in \textit{photonic digitizing devices} rather than in all-optical path devices controlled by non-optical means.

The inference property of a thin-film Fabry-Perot cavity is well known.\textsuperscript{7} The interference features can be used to produce an optically controlled gate, switching between ‘low’ and ‘high’ light intensities.\textsuperscript{4} This can be done by changing the medium within the cavity, i.e., tuning the cavity’s resonance.

Not following the common path, the purpose of this research was to investigate methods altering the electronic state - and therefore, the refractive index - of semiconductor materials large enough in order to be used as photonic switch or modulation. The approach in course of this dissertation was very straightforward: Two laser beams are crossed in the same spot in a thin-film semiconductor. One beam, the so-called control or write beam alters the local electronic state of the semiconductor in such a way that the intrinsic reflection of second beam, which is called the probe or read beam, is considerably changed. It is stressed here that the surface or the film-substrate interface of the samples has been used for laser crossing experiments. To avoid excessive heating of the film, and to minimize the dissipated power, relatively low power light sources should be used. Since operation at room temperature is obviously preferable, all research work was done at ambient conditions. Once an optical switch concept has been realized,
the assembly of a prototype of a logic gate is straightforward. Indeed, a single switch could serve as either an AND gate or an OR gate depending on the beams supplied to it. Whereas several currents in a single transistor inevitably become mixed, multiple light beams can pass through an interferometer without interaction – there are no photonic shortcuts. It would therefore be possible to utilize a single film for several distinct switching operations or modulations including more than two logical states.

A main challenge during the work was the acquisition of a reliable set of data accumulated with surface and interface excitations. Based on the experiments, it occurred that a simple model for both geometries cannot be applied since in many cases the surface showed different responses under the same experimental conditions in comparison to the interface. Finally, it is worthwhile to note at this point that the entire project was done at BGSU starting with the sample preparation using pulsed-laser deposition (PLD) and sophisticated combined optical and electronic measuring techniques were designed and built from the scratch for the specific measuring task. Consequently, a notable time input was required in order to start the experiments. The employed PLD equipment and the measuring setups used are described in chapter two and in subsequent sections.
1.2 Theoretical Consideration

1.2.1 Transmission of light in an absorbing medium

The theory of propagation of electromagnetic waves in an uncharged homogeneous material having a specific permeability, $\mu$, a dielectric constant $\varepsilon_1$ (real) and an electrical conductivity, $\sigma$, is based on Maxwell’s field equations, which may be written

$$\begin{align*}
\nabla \times E &= -\mu \mu_0 \left( \frac{\partial H}{\partial t} \right) \\
\nabla \times H &= \sigma + \varepsilon \varepsilon_0 \left( \frac{\partial E}{\partial t} \right) \\
\nabla \times E &= 0 \\
\nabla \times H &= 0
\end{align*}$$

Where, $\mu_0$ and $\varepsilon_0$ are permeability and real dielectric constant of free space.

The differential wave equation to be satisfied by the $E$-field is then,

$$\nabla^2 E = \mu \mu_0 \varepsilon_1 \varepsilon_0 \left( \frac{\partial^2 E}{\partial^2 t} \right) + \sigma \mu \mu_0 \left( \frac{\partial E}{\partial t} \right)$$

The harmonic wave satisfying the above equation may be represented by the expression:
\[ E = E_0 e^{i(\omega - \kappa r)} \]  

(1.3)

This satisfies the equation (1-1) provided

\[ \kappa = \left[ \omega^2 \mu_\varepsilon \varepsilon_0 - i \sigma \mu_0 \omega \right]^{\frac{1}{2}} \]  

(1.4)

Clearly the propagating vector \( \kappa \) is complex. Since the refractive index \( N \) is related to \( \kappa \) by

\[ N = c \omega^{-1} \kappa \]

The refractive index is also complex and can be given as,

\[ N = n - ik \]

Since \( c = [\varepsilon_0, \mu_0]^{\frac{1}{2}} \) the complex refractive index is

\[ N = \left[ \frac{\mu \varepsilon_i - i \sigma \mu}{\omega \varepsilon_0} \right]^{\frac{1}{2}} \]

For all cases of practical interest in optical properties we can take \( \mu \) to be unity. The real and imaginary parts of the complex refractive index are found in terms of frequency, electrical conductivity and dielectric constants by the equations

\[ n = \frac{\varepsilon_i}{2} \left\{ \frac{1 + \sigma^2}{\omega^2 \varepsilon_i^2 \varepsilon_0^2} \right\}^{\frac{1}{2}} + 1 \]  

(1.5)

\[ k = \frac{\varepsilon_i}{2} \left\{ \frac{1 + \sigma^2}{\omega^2 \varepsilon_i^2 \varepsilon_0^2} \right\}^{\frac{1}{2}} - 1 \]  

(1.6)
The complex dielectric constant $\varepsilon$ and the complex index of refraction $N$ are related through the following equation

$$
\varepsilon = \varepsilon_1 + i\varepsilon_2 = N^2 = n^2 - k^2 - 2i\kappa n
$$  \hspace{1cm} (1.7)

If the complex character of the wave vector, equation 1.2, is introduced into the harmonic wave, equation 1.1, the result is

$$
E = E_0 e^{-\frac{-\omega\kappa}{c}} e^{i\omega t - \frac{mr}{c}}
$$  \hspace{1cm} (1.8)

We conclude from equation (1.6) that wave propagates in the material at a phase velocity $c/n$ and is absorbed such that the amplitude decreases at a rate governed by the exponential form factor $\exp[-\omega\kappa c^{-1}]$.

Thus the real part $n$ must behave as the ordinary refractive index, and the imaginary part, $k$, called the extinction coefficient, determines the rate of absorption of the wave in the given medium which absorbs, but does not scatter. The power density $I \propto |E|^2$ and the absorption is usually described by the decrease in power density with distance, given by,

$$
I = I_0 \exp(-\alpha r)
$$  \hspace{1cm} (1.9)

Where $\alpha$, called the absorption coefficient, is related to the extinction coefficient $k$ by,
\[
\alpha = \frac{2\omega k}{c} = \frac{4\pi k}{\lambda}
\]  

(1.10)

The use of absorption equation (1.7) implies, however, that the intensities are to be measured within the absorbing medium and the total thickness of the medium is sufficiently large that there are no interference effects arising from multiple reflections.

Consider a plane wave incident normally on a surface \( z = 0 \). The co-ordinate system is shown in figure below.

![Figure 1.1 Reflection and refraction of light from an interface](image)

The complex indices of refraction of two media beside the surface are \( N_1 \) and \( N_2 \) where

\[
N_1 = n_1 - ik_1
\]

\[
N_2 = n_2 - ik_2
\]

Suppose the amplitude of the electric vector of the wave approaching the surface is \( E_1^+ \) and the reflected and transmitted waves are \( E_1^- \) and \( E_2^+ \) respectively. At the boundary, i.e., at \( z = 0 \), the point of incidence being the origin of the co-ordinates, the total components of the electric and magnetic vectors in the x- and y- directions are as follows:
\[ E_{1x} = E_{1y} = E_{1}^+ + E_{1}^- \]

\[ H_{1x} = -H_{1y} = [E_{1}^- - E_{1}^+] N_1 \]

For the medium below the surface

\[ E_{2x} = E_{2y} = E_{2}^+ \]

\[ H_{2x} = -H_{2y} = -E_{2}^+ N_2 \]

By applying the boundary conditions, one can obtain the Fresnel reflection and transmission coefficients \(r_1\) and \(t_1\), in terms of optical constants.

\[
\begin{align*}
    r_2 &= \begin{bmatrix} E_1^- \\ E_1^+ \end{bmatrix} = \begin{bmatrix} N_1 - N_2 \\ N_1 + N_2 \end{bmatrix} \\
    t_2 &= \begin{bmatrix} E_1^+ \\ E_2^+ \end{bmatrix} = \begin{bmatrix} 2N_1 \\ N_1 + N_2 \end{bmatrix}
\end{align*}
\]

(1.11) (1.12)

Therefore, \(r_1\) and \(t_2\) are also complex and can be represented as

\[
\begin{align*}
    r_2 &= g_2 + ih_2 \\
    t_2 &= 1 + g_2 + ih_2
\end{align*}
\]

Where,

\[
\begin{align*}
    g_2 &= \frac{n_1^2 + k_1^2 - n_2^2 - k_2^2}{M_2} \\
    h_2 &= \frac{2[n_1k_2^2 - n_2k_1]}{M_2}
\end{align*}
\]

(1.13) (1.14)

\[ M_2 = (n_1 + n_2)^2 + (k_1 + k_2)^2 \]
1.2.2 Fabry-Perot Etalon

Since its first introduction in 1899, Fabry-Perot Interferometer has profoundly influenced the development of thin-film optics.\(^7\)\(^9\) It belongs to a class of interferometers known as multiple beam interferometers since a large number of beams are involved in the interference. Suppose a collimated beam of monochromatic light of unit amplitude falls on a film which is parallel-sided, homogeneous and isotropic in absorption with a thickness of \(d\) and complex refractive index \(N_1\), let the substrate supporting the film has complex index \(N_2\) as shown in the following figure.

![Multiple Reflections from a Thin Film](image)

**Figure 1.2** Multiple reflections from a thin film

At the first surface, the incident wave is divided into two plane waves, one reflected and the other transmitted and the division process continues as shown in the figure. Real and imaginary parts of the three refraction indices are as follows
\[ N_0 = n_0 - ik_0 \]
\[ N_1 = n_1 - ik_1 \]
\[ N_2 = n_2 - ik_2 \]

The phase factor associated with the waves in the \( m \)th layer is of the form,

\[ e^{i\delta_m} = e^{\frac{i2\pi d_m}{\lambda} (n_m - ik_m)} = e^{\alpha_m} e^{i\beta_m} \]

where

\[ \alpha_m = \frac{2\pi d_m k_m}{\lambda} \]
\[ \beta_m = \frac{2\pi d_m n_m}{\lambda} \]

Therefore, the components of the electrical and magnetic vectors in the \( m \)th layer in the x- and y- directions are as follows:

\[ [E_m]_x = [E_m]_y = E_m^+ e^{-i\delta_m} + E_m^- e^{i\delta_m} \]
\[ [H_m]_x = -[H_m]_y = \{ E_m^+ e^{+i\delta_m} + E_m^- e^{-i\delta_m} \} N_m \]

Where, \( E_m^+ \) and \( E_m^- \) are the resultants of all positive going and negative going waves in the \( m \)th layer respectively.

Applying the boundary conditions the resulting equation can be expressed in terms of Fresnel coefficients in matrix form.
Where,

\[
[C_m] = \begin{bmatrix}
  e^{i \delta_m} & r_m e^{i \delta_m} \\
  r_m e^{-i \delta_m} & e^{-i \delta_m}
\end{bmatrix}
\] (1.16)

Since all the elements of the above matrix are complex, the \( m \)th matrix can be written as

\[
[C_m] = \begin{bmatrix}
  p_m + i q_m & r_m + i s_m \\
  t_m + i u_m & v_m + i w_m
\end{bmatrix}
\] (1.17)

For the case of a single film on a substrate shown in the following figure, the recurrence relation in equation 1.13 gives,

![Figure 1.3 Reflection and refraction from a single film on a substrate](image)

**Figure 1.3** Reflection and refraction from a single film on a substrate
\[
\begin{bmatrix}
E_0^+ \\
E_0^-
\end{bmatrix}
= [C_1][C_2]
\begin{bmatrix}
E_2^+ \\
E_2^-
\end{bmatrix}
\]  \hspace{1cm} (1.18)

By making the assumption that there is no negative going wave in the substrate, and therefore \(E_2^- = 0\) we can write:

\[
\begin{bmatrix}
E_0^+ \\
E_0^-
\end{bmatrix}
= [C_1][C_2]
\begin{bmatrix}
E_2^+ \\
0
\end{bmatrix}
\]  \hspace{1cm} (1.19)

Now the phase factor for the single film is given by

\[e^{i\delta_1} = e^{\alpha_1}e^{i\beta_1}\]  \hspace{1cm} (1.20)

where

\[\alpha_1 = \frac{2\pi d_1 k_1}{\lambda}\]  \hspace{1cm} (1.21a)

\[\beta_1 = \frac{2\pi d_1 n_1}{\lambda}\]  \hspace{1cm} (1.21b)

The Fresnel coefficients for the two interfaces can be obtained from equations 1.11 and 1.13.

\[r_1 = g_1 + ih_1\]  \hspace{1cm} (1.22a)

\[r_2 = g_2 + ih_2\]  \hspace{1cm} (1.22b)

\[t_1 = 1 + g_1 + ih_1\]  \hspace{1cm} (1.22c)

\[t_2 = 1 + g_2 + ih_2\]  \hspace{1cm} (1.22d)
Where

\[
g_1 = \frac{n_0^2 + k_0^2 - n_1^2 - k_1^2}{M_1}
\]  
(1.23a)

\[
h_1 = \frac{2n_0k_1^2 - n_1k_0}{M_1}
\]  
(1.23b)

\[
g_2 = \frac{n_1^2 + k_1^2 - n_2^2 - k_2^2}{M_2}
\]  
(1.23c)

\[
h_2 = \frac{2n_1k_2^2 - n_2k_1}{M_2}
\]  
(1.23d)

where \( M_1 \) and \( M_2 \) are given by

\[
M_1 = (n_0 + n_1)^2 + (k_0 + k_1)^2
\]

\[
M_2 = (n_1 + n_2)^2 + (k_1 + k_2)^2
\]

The reflectance \( Re \) is given by,

\[
Re = \left[ \frac{(E_0^-)(E_0^-)^*}{(E_0^+(E_0^+)^*} \right]
\]  
(1.24)

From equations 1.16 and 1.17

\[
Re = \frac{a_{12} + b_{12}}{p_{12} + q_{12}}
\]  
(1.25)
From equations 1.13 and 1.16

\[ Re = \frac{r_1 e^{i\delta_1} + r_2 e^{-i\delta_1}}{e^{i\delta_1} + r_1 r_2 e^{-i\delta_1}} \]

\( p_{12}, q_{12}, a_{12} \) and \( b_{12} \) can be determined in terms of \( g_1, h_1, p_2 \) and \( b_2 \).

\[ p_{12} = p_2 + g_1 a_2 - h_1 b_2 \]
\[ q_{12} = q_2 + h_1 a_2 - g_1 b_2 \]
\[ a_{12} = a_2 + g_1 p_2 - h_1 q_2 \]
\[ b_{12} = b_2 + h_1 p_2 - h_1 q_2 \]

For the reflectance case it is found that there exist minima of intensity, or destructive interference, when \( d \) is related to integral values of \( 2\pi \); that is, when the order of interference, \( m \), as defined below, has integer values:

\[ m = \frac{\delta}{2\pi} = \frac{2n_1 d}{\lambda} \]

Maxima, or constructive interference, will be found when \( m \) has half-integral values. The difference in thickness, \( \Delta d \), between successive maxima or minima, is useful in determining the real part of the complex index of refraction of the film.
\[ \Delta d = \frac{\lambda}{2n_1} \]  

(1.26)

The effect of absorption with increasing film thickness reduces the amplitude of successive maxima in the reflection curve. The width of the dark fringes observed in the reflection is governed by the value of reflectivity, \( r \), of each etalon surface (assumed to be equal) and for \( r \leq 1 \), their width is finite and given as a full width at half maximum by:

\[ a = \frac{1}{\sin[\sqrt{F}]} \]

Where \( F \) is called the coefficient of reflective finesse and is a function of reflectivity. 

\[ F = \frac{4r}{(1 - r)^2} \]
Chapter two

Experimental Setups

2.1 Introduction

The primary objective in this section is to give a brief introduction to the experimental setups used during the course of the study. This will include a basic schematic diagram and a description of the equipment used. While some of these setups were modifications of an existing system, most of the experiments were built from scratch for the required measurements. Some of the passive optical components such as band-pass filters, mirrors and lenses will be omitted from diagrams for clarity.

All control and data acquisition were done by computer, connected to the instruments via IEEE-488 communications port on the instrument and National Instrument GPIB interface card on the computer. The control software Kottan-Spec was used for photoluminescence, photocurrent, transmission and z-scan measurement. Measurements from numerous instruments were done simultaneously in most occasions.
2.2 Optical switch realized with cw laser sources

![Experimental setup for the steady state optical switch](image)

**Figure 2.1** Experimental setup for the steady state optical switch

The beams of the green and red lasers are crossed on the film surface or at the film/substrate interface, while measuring the reflected and transmitted intensity of the red beam. Two long-pass filters were used in front of the diodes to filter out the scattered green light. This turns out to be of utmost importance to the measurement since we are observing a reduction in the intensity of the red transmission, and any scattered light will work against the observed phenomenon, which is the down switch. The two photodiodes were connected to a picoammeter in order to measure the change in current. An electronically controlled mechanical shutter was used to block and unblock the green
The data from the ammeter were collected and recorded on to the computer through a GPIB communication card. Some relevant equipment specifications are as follows.

- Helium/Neon laser – JDM Uniphase wavelength stabilized with 10 mW maximum output at 633 nm. Linearly polarized.
- Argon/Krypton laser – Melles Griot 643 tunable wavelength. 20 mW maximum at 514.5 nm.
- Keithley 6485 Pico ammeter with GPIB communication port

Other hardware included Edmunds optics variable neutral density filter arrangement, 10 cm focal length convex lenses.

### 2.3 Nanosecond pulsed switch

![Experimental setup for the pulsed switch](image)

**Figure 2.2** Experimental setup for the pulsed switch
Same basic operation as the previous set up, but instead of the cw laser a pulsed laser is used to modulate the red beam. Since the width of the pulse was 6 ns, the conjunction of an ultrafast GaAs photodiode and an oscilloscope was employed to measure the photonic modulation of the reflected signal. A temporally resolved snap shot was captured and the data points were downloaded to a Microsoft Excel spreadsheet on the computer.

Equipment specifications

- Nd:YAG laser – Spectron SL456G emits laser pulses at fundamental wavelength of 1064 nm with a duration of 6 ns at a repletion rate of 10 Hz. For the switching purpose the radiation was upconverted to 532 nm. Maximum pulse energy of the fundamental is specified at 1100 mJ per pulse.
- Helium/Neon laser – JDM Uniphase wavelength stabilized with 10 mW maximum output at 633 nm. Linearly polarized at 500:1 with a vertical plane of polarization
- Oscilloscope – Hewlett-Packard Agilent 45610B with snapshot function and GPIB communication port to communicate with the computer.

A large number of screen shots had to be captured in order to get statistically founded data set. Neutral density filters were used to reduce the intensity of the pulses to prevent it from destroying the sample. The continuous (cw) power of the laser pulses were measured to be 2 mW before the density filters. The effective cw is further reduced by a factor of $10^{1.6}$ before striking the film surface.
2.4 Reflection and transmission measurements

[Diagram of experimental setup for reflection and transmission measurements]

Lock-in technique was applied to measure the transmitted and reflected light from the sample. This makes the measurements more accurate and reliable. A DC measurement could have replaced the lock-in with an ammeter and eliminated the optical chopper. We always applied lock-in technique to avoid offsets of straylight influences. Depending on the need of the spectral range we had two different setups to choose from.

For measurements in the range of 250 – 800 nm,

- Light source – CVI 150 W Xenon lamp
- CVI CM110 monochromator
- SRS 830 lock-in amplifier
- SCITEC optical chopper

For measurements in the range 400 – 1200 nm,
Light source – halogen lamp

SR 530 Lock-in amplifier

2.5 Reflection under laser illumination

![Diagram of experimental setup](image)

**Figure 2.4** Experimental setup for laser bleaching of monochromatic light

Since the light output from the monochromator comes out as an image of a vertical slit, the highly collimated laser beam has to be diverged in order to cover the complete projected image over the sample. A longpass or shortpass filter was used in order to prevent scattered laser light from reaching the photodiode; but this limits the usable spectrum of the monochromator.
2.6 Sample preparation- Pulsed Laser Deposition (PLD)

PLD is a “flash evaporation” method characterized by a very fast temperature rise in order to maintain the original target composition. The general design of a PLD setup is shown in Figure 2.5. A focused laser pulse with high intensity is absorbed by the target and creates a spot with high energy density. This causes a rapid temperature rise ($\approx 10^{12}$ K/s) followed by an explosive removal of material. The ablation can be of pure thermal origin and/or the chemical bonds of the target are broken by the impact of the high-energy. Depending on the laser parameters the charged particle cloud, i.e., the plume, is composed of atoms, ions, molecules or larger particle like clusters. Portions of these particles get singly or multiply ionized through the high temperatures and photoionization by the laser light. The expanding plume propagates in a direction predominately normal to the target surface until it reaches the substrate (glass or plastic) where the bonds are re-established by forming a thin film.$^{10-19}$
Chapter Three

Optical Switching

3.1 Introduction

This chapter opens up the discussion of optical switching by providing the essential background and a brief introduction to this subject. Reading through this chapter is not required to understand the entire thesis; however, it might be helpful in understanding some of the experimental approaches and data analysis. After all, the resulted research will be a possible future scenario of data transmission and telecommunications.

The tremendous development of new communication services and the ever growing internet have drastically changed the landscape of telecommunications industry. Innovations in the field of communication technologies and networking continue to unfold and will keep influencing the way we live. The principle building blocks of communication networks are communication terminals, transmission links, and switching centers. Switching is a cornerstone of communication system and has evolved, since the introduction of telegraphy and telephony in the nineteenth century until today.²⁰
3.2 The Original telephone network

By today’s standards, the early telephone network was primitive where users in a confined geographical region connected to other users by a single telephone set and copper wires. Each user needed some telephone sets and a number of copper-pair terminations. In the ideal situation, $N$ numbers of users are cross-connect with $N-1$ number of wire pairs in order to communicate with all the other users within the network (see Fig. 3.1 (a)). Then the multiple telephone sets were replaced by a switching mechanism to one set. The switching was merely a mechanism to manually connect the wires to the phone when a call is to be made to a particular user.

![Diagram](a) All users are connected to each other  
(b) Users are connecter through a switching center

**Figure 3.1** Introduction of switching in telephone networks

As the number of users increased, along with the distance separate them, this networking approach became complex, costly and unreliable. The need to build switching centers, telephone exchanges was then realized. Switching centers were usually centered within the geographical area they served and local telephone networks built around them$^{21}$. This
development is illustrated in Figure 3.1 (b). The job of the switching center is to connect any two subscriber lines as desired. As many telephone networks started to appear in this manner, the need for subscribers on one network to communicate with those on other networks also emerged. Hence, switching centers had to be interconnected via direct cable links or through another switching center. A typical telephone call in this network would go through one or several switching centers and each call reserved the entire end to end band width of the link. As more and more users joined the network more cable links between switching centers were needed. The initial and obvious solution for this at the time was to bundle up the copper wires into a one bulky transmission line, which was called multiplexing, specifically *Space Division Multiplexing* (SDM) and the concept of Multiplexing was born.

### 3.3 Multiplexing

Multiplexing is a technology where data from many transmission lines are funneled into one line and retrieved at the other end. The primitive form of this is SDM. This is essentially organizing the communication links in a space saving manner. A more elaborate form of this technology came out as *Time Division Multiplexing* (TDM) and *Frequency Division Multiplexing* (FDM). As the technology developed and with the advancement of transistors and integrated circuitry, the mechanical switching was replaced by electronic switching. With the advents of digital technologies and voice digitalization, multiplexing, transmission and switching migrated from analog to digital. Digital communication was fast, economical and provided improved voice quality.
In principle, both analog and digital signals can be multiplexed in either the frequency or time domain. However, it is easier to multiplex analog signals in the frequency domain and multiplex digital signals in the time domain. Therefore TDM gradually replaced FDM.

### 3.3.1 Frequency Division Multiplexing

With regard to telecommunication using a wired links, FDM is assigning each data link its own band width. A single copper wire is used to accommodate different data links, which have their own frequency. A more simplified but highly effective example is using free space for wireless communication. Each cellular carrier, radio station, TV broadcast make use of its own frequency to avoid cross-talks with each other and they all utilize the same medium.
3.3.2 Time Division Multiplexing

In TDM data or signals from different sources are sampled periodically and sent through a single link. This is also known as coding in different applications since the signal sent through the wire is coded in a specific way by the carrier. At the receiving end the signal is decoded and used to regenerate the original signals. Almost all modern electronics today operates on and utilize some sort of a TDM. One example is the speaker phone function of a telephone achieved by switching between microphone and speaker so as to avoid the feedback problem. A digital display panel only displays one segment at a time to save energy.

![Diagram of Time Division Multiplexing](image)

**Figure 3.3** Time Division Multiplexing

At any given time only one circuit is completed. The data selector sweeps through the inputs at a rapid rate and the de-multiplexer or the decoder regenerate the original signal at the receiving end. Multiple users are connected through one link. At its peak, one copper wire could connect few thousands of subscribers simultaneously.
3.4 Optical Networks and optical Switching

As the demand for telecommunication and data transmission grew in an alarming rate, the copper wire networks had a hard time keeping up. The electronics at the ends of a node had a far better band width and speed than the actual transmission line. This prompted the need for optical data communication networks. The copper wire was replaced by optical waveguides in the form of optical fibers. The electrical signal was converted to a light signal at the node and transmitted through the fiber. Optical communication links were faster, more reliable and substantially cheaper than its copper counterpart. With the development of Wavelength Division Multiplexing (WDM), a single strand of optical fiber could carry numerous data links with its own wavelength, carrying its own signal multiplexed in the time domain. This pushed the limits of the electronics at the switching nodes. The need to perform the switching at optical level was soon realized. Today, the term optical networks and optical switching are used to denote systems and networks that are not ‘optical’ in the full meaning of the word. The word transparency is used to define a network’s capability to perform its tasks on the optical level. A completely transparent network is capable of transferring any type of data only with photons without regard to protocol and coding formats. These are based on optical switching fabrics and are referred to as OOO or all-optical networks. In contrast to transparent, electrical networks are opaque.

Nowadays there are four major types of networks labeled as optical networks,

- **Optoelectronic networks** – only single-wavelength point-to-point transmission is carried out optically.
• **Opaque Optical networks** – networks where WDM is used leading to multi-wavelength optical transmission, while switching and control remain entirely in the electrical domain.

• **Partially transparent** – these are optical networks with varying degrees of transparency. The transparency is dependant on what percentage of the network operates primarily on optical level.

• **All-optical networks** – networks where all operations and functions, including switch control and network control, would be performed optically.

Only the last two types of networks in this list are indeed associated with optical switching. Even then the control is mostly done by other means. The most commonly used technology is MEMS based optical switches. This will be discussed in detail at a later section. So far it has been a challenge to implement controls in to optical domains.

**3.5 Optical switch**

Controlling the path of a light beam, either completely or partially terminating or diverting, is the purpose of an optical switch. This is the same as electrical switches are used in electrical circuits. The simplest form of an optical switch is realized by a mechanically controlled mirror. Though the mirror is controlled by non-optical means, the information carrying light beam is never converted to any other form. Interest in optical switching appeared for the first time in the 1970’s and increased in the 80’s after the inroads made by optical fiber to the telecommunication system. By early 90’s there were considerable amount of research efforts on optical switching. Contributions to this effort came from researchers in areas of electronic switching, optical and optoelectronic

29
devices, optical computing and optical communications\textsuperscript{25,26} by the end of 1990’s few primitive technologies were available to build optical switches for telecommunications\textsuperscript{27} guided-wave electro-optic switches (based on Lithium Niobate crystals), macro electro-mechanical switches, spatial light modulators (utilizing liquid crystals), and semiconductor optical amplifiers. As indicated earlier, the tremendous growth of the internet during mid to late 1990’s led to extensive deployment of WDM, provoking an outburst of regained activities in the arena of optical communication. Optical switching extends the reach of the virtually unlimited optical bandwidth, thereby elevating the information carrying capacity of the network to levels that are way beyond the possibilities of electronics.

### 3.6 Optical Switching Technologies

Due to the vast number of different technologies, it is almost impossible to classify them into clear cut categories. Some of them use more than one technique for switching (hybrid switches). Two generic types are usually recognized, the type based on guided wave optics (optical fiber and waveguides) and the other utilizing free-space optics. Based on the underlying physical effect that is responsible for switching, it can be categorized into following groups.\textsuperscript{28}

1. **Opto-Mechanical**: the commonly used technology in modern networks. Based mainly on free space optics, it comprises classical technological styles such as moving fiber and/or moving macro or microscopic optics. MEMS fall into this category. Though the light path is never converted into electric signal, the control of the beam is always done mechanically; hence the switching times are typically in the 100 ms range.
2. **Electro-Optic** - The most well known switching in this category is based on optical waveguides which are implemented on Lithium Niobate substrates and utilizes electro-optic properties of the material.

3. **Acousto-Optic** – this guided wave category exploits the acousto-optic properties of the switching fabrics and is mostly implemented on Lithium Niobate.

4. **Thermo-optic** – primarily based on the thermo optic properties of optical wave guides. Two main types of materials are deployed to implement these switches, namely, silica and polymers.

5. **Optical amplifier based switching** – both fiber and semiconductor based amplifiers have been proposed as switching devices. However, Semiconductor Optical Amplifiers (SOA) are more common in industrial applications and fiber based amplifiers are produced by some vendors for laboratory use.
Chapter Four

Photonic Digitizing

4.1 Making the Case for All-optical Switching

Continuing the discussion from the previous chapter, there is one major drawback in all of the described techniques; they all are hybrid switches. The control of light is predominantly done by electrical, mechanical, thermal or by some other external energy source. This is somewhat analogous to a mechanically controlled electrical switch such as a common household light-bulb switch. With the development of technology, mechanically controlled switches were replaced by electronically controlled ones, allowing the control of electricity by electrical means. Doing this in the optical domain—i.e. controlling light with light – was the main focus of this project. The term Photonic Digitizing or All-optical switching will give the meaning to this particular concept.

In the following sections a novel concept will be introduced which is not only technically undemanding but also simple and effective. So far the concept has been demonstrated with laser beams of moderate intensities. Essentially, the concept is a laser modulation technique which has the potential to be implemented as an all-optical switch or modulation tool.

According to equation 1.23 from chapter 1 the reflectance of the Fabry-Perot interferometer can be adjusted by changing the thickness of the film or the wavelength of
incident light. Neither method is of much value for optical switching. What is more important, the phase relation can also be changed by altering the optical properties of the film material. James Clerk Maxwell, in his fundamental work on electromagnetic radiation postulated that refraction and other interaction of light with matter are independent of the intensity of light. If this were always true, the refractive index (real) would be a constant and the output of the interferometer would be directly proportional to the intensity of the incident beam. Under appropriate conditions many substances yielded such result; they are said to be linear with respect to the refractive index (real). But, after the development of lasers it has been found that not all matter have a linear refractive index. When laser radiation is focused on certain substances, the refraction varies with intensity of the beam hence giving rise to non-linearity with respect to refractive index. With a nonlinear substance in the Febry-Perot cavity, the refractive index can be altered by changing the intensity of the incident beam. Initially the intensity of the probe beam (figure 4.1) is such that the refractive index yields an optical length corresponding to a minimum reflection which represents OFF state of the switch. If the intensity of the beam is increased, the refractive index and the optical path length change giving rise to an increase in reflection. The same effect can be achieved by illuminating the surface by another external source of light (a control beam). The refractive index variation will cause a change in the probe beam reflection giving rise to an optical switch. Therefore, the switching technique permits the control of a low power probe beam by the relatively high power control beam which works more efficiently if the reflectivity is low and the absorption is high at the wavelength of the control beam.
4.2 Laser modulation

The experimental arrangement for the steady state switch was described in Figure 2.1 of Chapter 2. The thin-film materials in discussion are Cadmium Sulfide (CdS), Zinc Telluride (ZnTe) and Gallium Arsenide (GaAs), which were deposited on glass substrates. Both the reflection and transmission modulations were evaluated. When ever possible the current passing through the photo diode was kept in the microampere range in order to minimize signal to noise ratio. Figure 4.1 and 4.2 illustrate a simple three dimensional rendering of the beam paths for the reflection and transmission experiments, respectively. The probe beam is perpendicular to the film surface in the transmission geometry and is impinging under an angle in the reflection arrangement.

![Figure 4.1 Beam paths for the reflection switch arrangement.](image-url)
The angle of incidence was kept at a possible minimum to avoid the effects due to non-perpendicularity.\textsuperscript{30,31} The modulation amplitude is defined as the percentage of change in the reflected read beam. The direction of change was positive or negative depending on the final intensity of the reflected probe beam.

![Figure 4.2 Beam paths for the transmission switch arrangement.](image)

The modulation amplitude $MA$ is given by,

$$MA = \frac{(I_i - I_f)}{I_f} \times 100,$$

Where, $I_i$ is the initial photocurrent and $I_f$ the final photocurrent. The responsivity of the photo diode was found to increase in a linear way with the incident intensity, at a given wavelength. Consequently, the current change of the photodiode corresponds to the intensity change.
For each experiment, two sets of data were recorded. The reflection and transmission changes from the film surface and from the substrate film interface, except for the case of GaAs on plastic. The later showed only transmission switch (under steady state conditions) with an almost undetectable reflection modulation. This special case will be discussed in the relevant section. In all of the following plots the photocurrent of the diode (y-axis) will be normalized for enhanced clarity. Though there were a vast number of data sets for the same experiment, the ones with the lowest noise levels and best reproducibility are be presented and discussed. A typical data file was processed using plot programs such as Origin or Kaleidagraph. All of the experiments were done at room temperature.
4.2.1 Results for CdS with cw lasers

![Graph](image)

**Figure 4.3** Surface reflection and transmission modulations of a CdS/plastic sample using cw lasers.

Figure 4.3 reveals negative logic (see p.35) using reflection from the film surface and a positive transmission logic through the film. A clearly resolved reflection digitizing with a 25% modulation depth and transmission switch with 1% was observed, using the laser lines at 632 nm (HeNe, 8 mW) and 532 nm (DPSS, 6 mW) as probe and control beams, respectively. The time resolution of the data collecting arrangement was 100 ms (i.e. at a rate of 10 data points every second). The reaction time and relaxation time of the switch might have been over shadowed by the overall slow response time of the setup. A more thorough analysis will be done about the relaxation times in the section for the switch.
under real-time conditions where no mechanical shutter was used. The above shown results are from a sample of thin-film CdS on a plastic substrate\textsuperscript{32}. Similar results were achieved with variations in modulation depth for films on glass substrates. Some noticeable behaviors of modulation direction and amplitude depending on the incident power and wavelength of the laser will be discussed in a later section.

![Figure 4.4](image-url)  
**Figure 4.4** Reflection and transmission modulations from a film/glass interface of a CdS/glass sample using cw lasers.

In contrast to fig. 4.3, both transmission and reflection decreased by crossing the lasers at a glass-CdS film interface, as illustrated in fig. 4.4.
4.2.2 Results for ZnTe on glass

![Normalized Transmission vs Time plot](image)

**Figure 4.5** Normalized surface reflection and transmission for ZnTe/glass.

Figure 4.5 reveals the negative transmission digitizing (8%) and positive surface reflection modulation (2%) achieved with ZnTe on glass. The laser beam crossing point was on the film surface of ZnTe. Control beam was the 530 nm line of an Ar/Kr laser (15mW) and the probe beam was the 633nm line of a HeNe (8 mW). Though the switch amplitude is small, the important factor worth noticing is the opposite directional modulations of the transmitted and reflected beams with respect to other results. In fact,
the behavior shown in fig. 4.5 was only seen with ZnTe (and GaAs to an extent) while CdS has a switch down in reflection and switch up in transmission(see fig. 4.3). Higher modulation amplitudes were achieved from setting up experiment specifically for either reflection or transmission (Figure 4.1 and 4.2).

On the other hand the film glass interfaces revealed a more prominent switch.

![Figure 4.6](image)

**Figure 4.6** Normalized reflection and transmission for ZnTe/glass on the film – glass interface.

Figure 4.6 shows the reflection and transmission switches using the film/glass interface as LC medium under the following experimental parameters. The control beam was the 514.5 nm line from Ar/Kr laser (5mW) and the probe beam – 632.8 nm line of a HeNe
(8 mW). The MA for reflection is 2% and close to 20% for transmission.

To investigate whether there are significant changes in the switch performance depending on the substrate used, thin-film ZnTe on ITO was put to test. There was no particular reason for using ITO in place of glass other than its transparency.

Results for the film surface experiment for ZnTe/ITO are shown in Figure 4.7. The noticeable difference is the complete disappearance of the reflection modulation. The plot is for a control beam at 530 nm of 16 mW switching a beam at 632.8 nm of 8 mW. The transmission exhibits 13% modulation amplitude while reflection modulation was not observed even with various wavelengths and different powers. This was expected since

Figure 4.7 Normalized interface reflection and transmission for ZnTe/ITO.
the bulk of the incident light is reflected from the highly reflective ITO surface and the change in reflectance from the film surface was virtually non-existent.

On the other hand a small reflection switch (<1%) was observed by crossing the laser rays at the film/ITO interface. The experiment was repeated a number of times to verify the validity of above results. Each time the same results have been seen within the experimental errors.

**Figure 4.8** Normalized surface reflection and transmission for ZnTe/ITO
4.2.3 Results for GaAs on glass

GaAs was the most tested material during the time of the project and by far, produced the most appealing and promising results. Three different samples were put to test. The outcome of one set is presented in the following.

Figure 4.9 Normalized surface reflection and transmission switch for GaAs/glass.

Compared to ZnTe and CdS, the MA is relatively small (~2%) for the GaAs film surface reflection. This was also apparent in the GaAs film/glass interface reflection which can be seen in figure 4.10. Transmission MA was close to 8%, while for reflection it was less than 2%.
As similar to the previous figures, in fig. 4.9 the low resolution of the data acquisition system is evident by the ‘digitizing steps’ of the reflected signal.

Figure 4.10 Normalized reflection and transmission switch for GaAs/glass from the glass-film interface

In comparison with the CdS reflection digitizing the sign of the logic is the opposite, i.e. the reflection goes in the positive direction.
4.3 Rationalization of the cw laser modulation

The operation of the semiconductor switch is loosely based on the capability of the control beam to create free carriers in the semiconductor, hence giving rise to reversible photo-induced changes in optical transmittivity and reflectivity, absorption edge shift$^{24-29}$ and index of refraction.$^{33-35}$ Previous papers discussed the theory of reflection$^{36}$ and transmission$^{37}$ switching under somewhat similar conditions. Since laser irradiation of sufficient photon energy can produce high free carrier densities on a picosecond time scale, the reflection properties of a semiconductor can also be changed in the same time scale. This will be discussed further in a subsequent section.

Free carriers can be generated from exciting the film by laser illumination where milliwatt power beams can readily create densities $>10^{15}$ carriers/cm$^3$. Such excess free carriers can have a number of effects.$^{38}$

1) Alteration of the complex dielectric constant: Hence change in refractive index.

2) Screening of excitons: At low temperatures and in pure material the absorption spectrum at photon energies near the gap generally shows exciton features. Introduction of free carriers can ‘screen out’ these effects effectively saturating the absorption and changing the dispersion. However, this effect is less important in narrow gap materials, particularly above helium temperatures.
3) Perturbation of the energy states: this may occur due to many-body effects arising due to free carrier scattering. Thus, the introduction of excess carriers generally leads to a band-gap reduction.

4) Band filling: despite the initial energy of the laser-induced excess carriers, they thermalize on a timescale controlled by intra-band recombination, and on the order of picoseconds, until they fill the lowest (highest) conduction (valence) states. This blocks optically absorbed direct transitions and affects the refractive index.

Thus, under illumination by photons with energy exceeding the band-gap energy, an excess carrier density is created in the surface layer of the corresponding thickness. With intense illumination, it is possible to produce free surface carrier densities sufficient to enhance the reflection of the probe beam. This can possibly account for the observed reflection modulation.

But one must acknowledge the fact that highly amorphous films which were used in the experiments do not possess the band structure of a crystal. Hence, depending on the point of the surface used for the experiment the outcome might vary due to the complex surface morphology. If the above statement holds, increased intensities and higher photon energies of the control beam should give rise to a more pronounced reflection switch.

With reference to the transmission switch, photo thermal effects are not significant for the observed switching phenomena due to the low powers of the laser beams and, again is interpret the switch as an alteration of the electronic state in the bulk of the material. In general, the absorption coefficient of a semiconducting material depends on the difference \([f(E_f) - f(E_{u})]\) where \(f(E_f)\) and \(f(E_{u})\) represents the
occupation probability of the lower and upper energy levels involved in the transition. For the case of GaAs, the laser energies employed excite the film non-resonantly far into the conduction band. Consequently the important energy level for our consideration is $E_i$ and the observed switching requires an increase in $f(E_i)$; i.e., the additional laser irradiation excites supplementary previously trapped carries causing further alterations to the complex refractive index changing the absorption of the film. It is stressed that the switching phenomenon should be understood as an integral kinetic change of the absorption transition at certain energy due to an additional optical perturbation of the electronic state and should not be explained by fixed and defined transitions in space and time. Furthermore the observed switch is not merely a consequence of a single physical phenomenon but rather a collection of effects within the material due to its highly complicated structure.
4.4 Switch Characteristics

In an attempt to better understand the underlying principle of the switching concept, various experiments were performed such as investigation of reflectance changes in the probe beam due to intensity and wave length variations in the control beam. In order to explore the potential of the concept to be used as a hybrid switch, the modulation characteristics were observed under an applied electric field as well. One of the more important experiments that needed to be performed was to study the behavior of the switch due to the change in film thickness. There were many occasions where the same experimental parameters produced different switches when the focus point of the sample was changed. This could be due to the texture and composition variations on the film surface and also due to thickness changes.

4.3.1 Intensity Dependence

Employing a series of neutral density filters, the intensity of both control and probe beam could be changed in known quantities. The goal was to study the behavior of modulation with the intensity change of the impinging laser light. For reliability and secure use of the laser crossing for technological applications, it is of great interest to check whether the switch contrast sensitively depends on the intensities of the involved laser beams. The following figures are for a thin film of GaAs on Glass under the standard configuration, i.e., the film surface was facing the incoming beams.
Figure 4.11 GaAs/glass: dependence of the green transmission (probe beam) on green and red (control beam) intensity.

Figure 4.12 GaAs/glass: dependence of the red transmission (probe beam) on green (control beam) and red intensity.
Figure 4.11 summarizes the results for transmission modulation where the 532nm Ar/Kr line is the probe beam and 632.8nm HeNe line is controlling the switch. The data reveal that the modulation does not appreciably depend on green beam intensity, i.e., the red laser excites carriers out of a different reservoir than the green beam. They further demonstrate that Modulation amplitude linearly increases with the power of red laser. Further experiments were performed in the same way as those in figure 4.11 but inverting the role of the two lasers. The results are shown in figure 4.12 and confirm the same qualitative behavior as the findings in figure 4.11 but with higher modulation amplitudes. In order to compare the two switching fabrics, GaAs and ZnTe, we chose to switch the red laser with the green laser in both reflection and transmission geometries since this configuration gives the most prominent modulations. Figures 4.13 and 4.14 show the results.

![Graph showing reflection modulations at various incident powers of the control beam.](image-url)
The results in the above figure are for a 7 mW probe HeNe beam at 633nm and a control beam at 532 nm coming from Ar/Kr laser of 22 mW, while neutral density filters have been used to change the intensity. The almost linear relationship between the control intensity and probe modulation depth is very promising for potential applications. It is also evident that a threshold intensity (~1 W/cm$^2$) is needed to provoke the modulation in the first place. This emulates an optical transistor with the probe beam being the collector emitter path and the control beam, the base. The not so highly reflective CdS sample did not demonstrate such results since the modulation amplitude was very low (<1%) to start with and did not increase substantially with the intensity increase of the control beam.

**Figure 4.14** Transmission modulations at various incident powers of the control beam.

Above figure shows the transmission switch for various powers of control beam for the same parameters as in figure 4.13. The switch for the GaAs surface tends to level off
beyond 1 W/cm² intensity. The results achieved from the film/glass interface corresponds with the above presentations but with significantly higher modulation numbers.

### 4.3.2 Wavelength dependence

To study the switch behavior depending on the wavelength of the control beam, different laser lines of a tunable Ar/Kr laser was employed in conjunction with the 633nm line of the HeNe laser. Measures were taken to keep the intensity of each line comparable.

![Graph](image)

**Figure 4.15** Reflection and transmission modulation of ZnTe/glass versus photon energy exciting (a) the film surface (b) the film glass interface

Figure 4.15 shows the photon energy dependence of reflection and transmission modulation achieved by exciting (a) the film surface and (b) film/substrate interface of a ZnTe/Glass sample. In the case of reflection, for both geometries the modulation amplitude stayed fairly constant with the change of the control beam wavelength, while the transmission modulation was clearly increasing approaching red light in figure 4.15.
(b). As discussed earlier, we attribute the origin of the transmission switch to reversible photo-induced changes in the bulk of the material, thus the sample penetrating red light causes more electronic alterations in the bulk than green light absorbed at the surface. In both cases the reflection switch was minimal and stayed constant.

![Graph showing transmission modulation vs. wavelength (nm)](image)

**Figure 4.16** transmission modulation of ZnTe/glass. Excitation took place a) at the film surface and b) at ZnTe/glass interface

Figure 4.16 illustrates the appealing results achieved with thin-film ZnTe on ITO. If laser crossing was performed on the film surface, the transmission modulation decreased while increasing the wavelength of the control beam. Excitation of the interface revealed the opposite behaviour.
4.3.3 Opto-electric hybrid switch

So far, the thin-film semiconductors were used as a passive element for laser crossing and the intrinsic properties under various geometries were exploited in order to realize modulation via laser crossing. Here the film was used as an active hybrid element by applying an electric field along the film surface during optical excitation.

![Schematic for the hybrid operation.](image)

**Figure 4.17**: Schematic for the hybrid operation.

In order to transform the passive film to an active device, two aluminum contacts were evaporated on to the film surface. The gap between the contacts is typically around 1 mm and applying a bias of 500 V results in an electric field of 5 kV/cm. Figure 4.18 and 4.19 show the results for ZnTe/glass, using the film surface and interface as laser crossing media, respectively.
**Figure 4.18:** a) Reflection and b) Transmission modulation of ZnTe/glass as a function of the applied electric field. The laser beams have been crossed at the film surface.

**Figure 4.19:** Equivalent a) Reflection and b) Transmission experiments as the ones in fig. 4.18 exciting the interface of the sample.
Due to the high resistance between the contacts (~5 MΩ) the dissipated electrical power through the film was less than $10^4$ W. The presumed reason for the modulation decrease with the increase in electric field is the reduction of the number of electrons available for absorption transitions, i.e., with growing electric field more and more electrons join the circulation of the photocurrent rather than maintaining the overall matrix element of the sample absorption. A previous study done with GaAs on glass has shown that the switch can be inverted by applying a sufficiently strong electric field$^{41}$. However it is less technologically appealing to use high voltages.
4.5 Pulsed Laser Modulation

As discussed in the introduction, the laser crossing concept requires fast (~ps) response times in order to be considered in the photonic switching arena. In order to check the temporal capabilities of the concept, the continuous wave control beam was replaced by a Nd:YAG laser (6 ns, 10 Hz) with a peak intensity of about 4 MW/cm². The experimental setup described in figure 2.2 was employed to capture the time resolved reflection modulation. An oscilloscope (500 MHz) connected to a fast GaAs photodiode (rise time 10 ps) enabled a temporally resolved snapshot.

![Figure 4.20](image)

**Figure 4.20** Temporally resolved reflection modulation of red laser light from the surface of CdS/plastic caused by 6 ns pulses at 532 nm of a Nd:YAG laser

Figure 4.20 presents results of such an experiment done with a sample of thin-film CdS on plastic. The dotted vertical lines represent the control beam pulse, while the time varying signal is the reflection of the HeNe beam from the CdS film surface. The 532 nm YAG pulses do not provide the same output intensity in every pulse. It is clearly evident
from the graph that higher intensity pulses yield deeper modulations in the red beam reflection. The average measured cw power of the YAG laser pulses was 2 mW and was focused onto the sample resulting in an intensity less of than 1 W/cm². The reaction time of the switch was on par with the rise time of the pulse while the recovery time turns out to be comparatively slow. To measure the recovery time, a single switching event was plotted figure 4.21. The recovery time is the span from 90% to 10% of the modulation amplitude.

![Graph](image)

**Figure 4.21** Reflection modulation recovery time of the CdS/plastic.

A comparison between laser pulse and response of the CdS sample is shown in Fig. 4.21. The modulation shows negative modulation instantaneously following the laser pulse, i.e., at least with the same temporal speed as the photodiode rise time, while the recovery takes place within 40 ms. The modulation depth achieved was typically around 5%. Comparable reflection modulation experiments were done using GaAs/plastic. Figure 4.22 reveals the modulation for four complete cycles. The YAG pulses were removed from the plot since all the switches have more or less the same amplitude.
The above results were achieved with very low laser intensities due to the fact that GaAs surface is highly absorptive and even a slight increase in laser fluence damaged the sample. Consequently the continuous power of the YAG pulses was kept below 1 mW.
Figure 4.23 shows a comparison between laser pulse and response of the reflection switch for GaAs sample.

Figure 4.24 shows a real time measurement for the GaAs sample in comparison with the result for CdS. The recovery time of the negative spike is notably reduced (10 ms) with GaAs but the response shows after the recovery of the negative spike a slightly positive signal for about 20 ms. Furthermore, the measured modulation amplitude of typically 2% is below the result for CdS. Part of these differences are attributed to the fact that, in contrast to the CdS film, the GaAs film is opaque for the laser sources used and the
irradiation is highly absorbed in the surface region, hence, the intensity was kept at a minimum to avoid a destruction of the sample.

4.6 Reflection pattern variations

As mentioned in a preceding section a cw reflection switch was not achieved with some of the samples investigated. Further experimentation revealed that under these conditions, rather than an intensity variation, a clearly visible pattern change, somewhat similar to self focusing\textsuperscript{42}, occurred in the reflected beam. The steady state switch was performed with lasers emitting at 633 nm (probe) and a 532 nm (control) and instead of the photodiode, the reflected beam was projected onto the wall. The captured reflection patterns are presented in Figs. 4.25 (a), 4.25(b) and 4.26 (a), 4.26 (b).

Figures 4.25 (a) and 4.25 (b) show the He-Ne laser reflection pattern from the CdS surface without and with additional cw green laser irradiation, respectively. The reflection pattern hardly changed, whereas, the reflection pattern of the GaAs film considerably underwent an alteration as demonstrated in Figs. 4.26 (a) and 4.26 (b), which show the intrinsically reflected laser spot and its variation under additional green cw laser irradiation, respectively. It is stressed that the intensity of the geometrically reflected ray did not undergo a considerable change since the photodiode used showed hardly a change in the photocurrent.

We attribute the dissimilar reflection characteristics of the samples to differences in the surface topographies, which were visualized with an Atomic Force Microscope (AFM). Figures 4.27 (a) and 4.27 (b) reveal the AFM images for CdS and GaAs, respectively. Comparing the two images, the different surface morphologies are obvious.
The CdS surface appears to be more compact and of a fairly mosaic texture while the GaAs surface is composed of local cluster accumulations. Considering the thickness of both films, the CdS film seems to have a much smaller thickness to surface-roughness ratio than the GaAs film. As a consequence, we believe that photo-induced local electronic effects such as charge redistributions (which locally modify the refractive index) in the GaAs clusters might be the origin of the considerable reflection pattern alteration.
Figure 4.25 (a)
Reflection of the red laser from the CdS surface with the green control laser off.

Figure 4.25 (b)
Same as Fig. 4.25(a) but the control laser on.
Figure 4.26 (a) red laser reflection pattern from a GaAs film surface with control laser off

Figure 4.26 (b) Reflection pattern similar to Fig. 4.26(a) with control laser on
Figure 4.27 (a) Atomic Force Microscopy surface image of CdS.

Figure 4.27 (b) Atomic Force Microscopy surface image of GaAs.
Chapter Five

Reflection Coefficient Measurements

5.1 Transmittance and Reflectance of a thin film

The surface reflection coefficient ($R$) is an important intrinsic optical property of a thin-film material. The amount of light reflected and transmitted through the film directly depends on $R$ which is a unit-less number within unity. In some literature, it is also expressed percent. By measuring the reflectance ($Re$) and transmittance ($Tr$) of the film, one can calculate $R$ of the material to a very high degree of accuracy. $Tr$ and $Re$ can be defined as:

\[ Re = \frac{I_{ref}}{I_0} \]  \hspace{1cm} (5.1)
\[ Tr = \frac{I_{Tr}}{I_0} \]  \hspace{1cm} (5.2)

Where, $I_0 =$ Intensity of the incident light

$I_{ref} =$ Intensity of the reflected light

$I_{Tr} =$ Intensity of the transmitted light
We can also derive $Re$ and $Tr$ in terms of the reflection coefficient by considering a thin film with a thickness $d$ and with an absorption coefficient $\alpha$.

![Figure 5.1](image_url)

**Figure 5.1** multiple internal reflections of a thin solid film with thickness $d$ and absorption coefficient $\alpha$

By ignoring the higher order terms and from eqn.4.1 we can write,

\[
Re = R\{1 + (1 - R)^2 \exp(-2\alpha d)\}...........................................(5.3)
\]

and

\[
Tr = (1 - R)^2 \exp(-\alpha d)...........................................(5.4)
\]
Considering the thickness of the film we can safely assume that $\alpha$ stays the same for both the above equations. Combining 5.3 and 5.4 we can derive an equation for $R$ that depends only on $Tr$ and $Re$. (See Appendix A).

$$R^3 - (2 + Re )R^2 + (2Re + Tr^2 + 1) - Re = 0............................(5.5)$$

By solving the above equation (see Appendix A) for measured values of $Tr$ and $Re$ at a given wavelength of incident light, one can calculate the reflection coefficient to a good degree of accuracy. For 532 nm light on a CdS thin-film on plastic substrate yields a reflection coefficient value of 0.14, which falls right in line with published values

The experimental setup 1.3 described in chapter 1, was utilized to study the dependence of $R$ on the photon energy of the incident light. In the following sections I will present and discuss the observations for different material in more detail.

5.2 Reflection coefficient of CdS

The intensities of the reflected and transmitted ($I_{Re}$ and $I_{Tr}$) light were measured from the surface of a thin-film CdS on plastic substrate. A 1.0 optical density filter was used in front of the monochromator to further reduce the intensity of the monochromatic light by a factor of 10. This prevented the lock-in amplifier from going into the overload. Figure 5.2 shows the $I_{Re}$ and $I_{Tr}$ measurements with the variation of wavelength. Measurements were carried out in 2 nm intervals from 450 nm to 720 nm. Measuring $I_0$ and using equations 5.1 and 5.2 we can calculate and plot the dependence of $Re$ and $Tr$ on the wavelength of the incident light. Since the monochromator does not give out the same intensity for the whole spectrum, especially in the case of the Xenon lamp $I_0$ is also
measured (Figure 5.3) for the span from 450 nm to 720 nm in the same 2 nm intervals. The incident angle was kept below 15 degrees in order to minimize the affects of angle dependence\textsuperscript{30,31}. This also paves the way to use this reflection coefficient data to calculate the refractive index by means of a simple equation.

![Graph of Wavelength dependence of the reflected and transmitted intensities of CdS/plastic](image)

**Figure 5.2** Wavelength dependence of the reflected and transmitted intensities of CdS/plastic

From equations 5.1 and 5.2 reflectance and transmittance is calculated. Figure 5.3 shows the results.
Figure 5.3 Reflectance, transmittance and absorption of thin-film CdS vs. wavelength

The line for absorption = [1 - (reflectance + transmittance)], is calculated using energy conservation which will also account for the scattered light from the film. The discontinuity of the reflection line near 590 nm and 660 nm turns out to be an intrinsic feature of the monochromator which is also visible in figure 5.2.

Using equation 5.5 we can calculate the reflection coefficient $R$ for each wavelength. The results are shown in figure 5.4. A dip in $R$ near the band gap of CdS is clearly visible.
Due to the highly opaque nature of the ZnTe and GaAs film, transmission of the monochromatic light through the material was virtually non-existent. Hence the same plot could not be obtained for ZnTe and GaAs.

5.3 Laser bleaching of the reflectance of ZnTe, GaAs and CdS

The next obvious step was to perform the whole experiment with supplementary laser illumination on the reflection spot on the sample, in order to calculate the reflection coefficient change due to the additional laser excitation. If the switch is to be successful in handling wavelength division multiplexing, the change should preferably be uniform within the range. However due to experimental constrains, reliable results could not be achieved for transmission change of the CdS film. The extra laser illumination caused
saturation of the photodiode, forcing the Lock-in amplifier to overload. Therefore only the reflection change was measured and will be presented in following figures.

Successful results were obtained for ZnTe on glass, which showed significant interference fringes for the monochromatic light.

Figure 5.5 Change in reflectance of ZnTe/glass due to additional laser irradiation.

Reflection of the monochromatic light was measured from 600 nm to 800 nm (a) without any additional illumination on the sample and (b) illuminating the spot with a 530 nm DPSS laser. A concave lens was used to diverge the beam to an area of about 1 cm$^2$ on the sample which effectively covered the monochromatic light reflection spot. The
impinging laser intensity was 50 mW/cm². the change in reflectance is clearly visible in Fig. 5.5 although the change disappears above 700 nm. The 532 nm laser excites the sample near its band gap (~ 550 nm) and the induced change maybe more prominent in that region. The Fabry-Perot interference of line (b) is not pronounced due to the roughness of the surface. On the other hand ZnTe on plastic substrate yielded less noisy results.

![Graph](image)

**Figure 5.6** Reflectance vs. incident wavelength for ZnTe on plastic

In figure 5.6, reflectance variation due to laser illumination is clearly visible. Again the change is more prominent in the vicinity of the band gap and vanishes around 850 nm.
Figure 5.7 Reflectance vs. incident wavelength for GaAs on plastic

Figure 5.7 shows the results for GaAs/plastic. The reflectance change is <1% due to the additional light laser on the sample. But when the switching experiment was performed, the intensity of the control beam reached \( \sim \text{W/cm}^2 \) whereas the diverging laser light here only comes close to 50 mW/cm\(^2\), easily three orders of magnitudes smaller.
Figure 5.8 Reflectance versus incident wavelength for CdS on plastic

Figure 5.8 shows the optical bleaching experiment for CdS on plastic. Like in Fig. 5.7, only a subtle effect is visible.
Chapter 6

Conclusions and Future Work

6.1 Conclusions

We have presented a simple and straightforward photonic digitizing method with laser beam crossing using thin-film semiconductor on different substrates. The same switch fabric has been utilized as either a reflection or a transmission laser modulator. It is further demonstrated that the switch characteristics can be easily manipulated by changing the experimental parameters such as laser intensities and wavelengths. Very promising results have been achieved by influencing the switch with an applied electric field, recognizing the hybrid operation capabilities of the concept. Furthermore, it has been shown that reflection modulation can be achieved with nanosecond rise time using laser pulses. The change in the reflectivity spectrum of the films under laser illumination was observed for all three materials with more prominent changes in ZnTe. Due to the unique surface characteristics of the GaAs film, pattern variation of the projected reflection under laser illumination could be observed. This might lead to pattern related optical switch techniques.
6.2 Summary of results

Table below summarizes all the results for cw laser modulation presented in previous sections.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Transmission Switch (%)</th>
<th>Reflection Switch (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Film surface</td>
<td>Interface</td>
</tr>
<tr>
<td>CdS on glass</td>
<td></td>
<td>2↓</td>
</tr>
<tr>
<td>ZnTe on glass</td>
<td>9↓</td>
<td>18↓</td>
</tr>
<tr>
<td>GaAs on glass</td>
<td>8↓</td>
<td>8↓</td>
</tr>
<tr>
<td>CdS on plastic</td>
<td>&lt;1↑</td>
<td></td>
</tr>
<tr>
<td>GaAs on plastic</td>
<td>7↓</td>
<td></td>
</tr>
<tr>
<td>ZnTe on ITO</td>
<td>12↓</td>
<td>10↓</td>
</tr>
</tbody>
</table>

↑ - denotes positive switch

↓ - denotes a negative switch
6.2 Applications and future work

One straightforward application potential of the laser modulation method is realization of logic gates. In the following a simple setup is described that was used to replicate the logic NOR operation. The 530 nm line of the Ar laser was used as the control beam and the probe beam was the 632 nm HeNe line. With a semi-mirrored beam splitter, the control beam was split into two rays, which could be turned on and off with mechanical shutters.

![Diagram of laser crossing to realize logic NOR operation]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 6.1** employing laser crossing to realize logic NOR operation

These two beams represent the two inputs, A and B. Output is the red transmission through the film. Figure 6.1 shows the results for the NOR operation. We define appropriate intensity level as logic “1” and anything below that as logic “0”. The result can even be interpreted as a logic device having more than two levels. The levels depending on the percentage of the beam splitter used, i.e., a 50% beam splitter will yield an intermediate logic level that is right in the middle of “1” and “0”.

78
Figure 6.2 Logic NOR realization using laser modulation

With all positive features of this concept there are however some inevitable drawbacks. The most important being the need for highly collimated beams and all the optics that has to accompany open beam paths. One possible way to avoid this is to replace open beams with optical fiber. Eliminating the separate switch fabric altogether and depositing thin-film semiconductor on the cross section of the optical fiber is also a possibility. We already have demonstrated that it can be successfully deposited on plastic foil, which produce far better modulations than thin films on glass.
APPENDIX A

Derivation of the reflection coefficient in terms of reflectance and transmittance

\[ Tr = (1 - R)^2 \exp(-\alpha d) \] ........................................(1)

\[ \frac{Tr}{(1 - R)^2} = \exp(-\alpha d) \]

\[ \frac{(1 - R)^2}{Tr} = \exp(\alpha d) \]

\[ \ln\left(\frac{1 - R}{Tr}\right) = \alpha d \]

\[ \alpha = \frac{1}{d} \ln\left(\frac{1 - R}{Tr}\right) \] ...........................................(2)

If we only consider up to the second order reflection,

\[ R_s = R \{1 + (1 - R)^2 \exp(-2\alpha d)\} \] ..............................(3)

\[ \left(\frac{R_s}{R} - 1\right) \frac{1}{(1 - R)^2} = \exp(-2\alpha d) \]

\[ \frac{R_s - R}{R(1 - R)^2} = \exp(-2\alpha d) \]

\[ \alpha = \frac{1}{2d} \ln \left(\frac{R(1 - R)^2}{R_s - R}\right) \] ...........................................(4)
by combining (2) and (4),

\[ \frac{1}{2d} \ln \frac{R(1-R)^2}{R_e - R} = \frac{1}{d} \ln \frac{(1-R)^2}{Tr} \]

\[ \sqrt{\frac{R(1-R)^2}{R_e - R}} = \frac{(1-R)^2}{Tr} \]

\[ \sqrt{\frac{R}{R_e - R}} = \frac{(1-R)}{Tr} \]

\[ \frac{R}{R_e - R} = \frac{(1-R)^2}{Tr} \]

\[ R * Tr^2 = (R_e - R)(1 - 2R + R^2) \]

\[ Tr^3 R = R_e - 2RR_e + R_e^2 - R + 2R^2 - R^3 \]

\[ R^3 - (2 + R_e)R^2 + (2R_e + Tr^2 + 1) - R_e = 0 \]

The roots of this equation will yield the reflection coefficient for given values of reflectance and transmittance.

A simple Mathematica routine yields the three roots of the equation, two complex solutions and one real solution.

\[ \text{Solve}[x^3 - (2 + r) x^2 + (2r + t^2 + 1) x - r = 0, x] \]

Where \( R_e = r \) and \( Tr = t \)

By using measured values of \( r = 0.257 \) and \( t = 0.7 \)
\[ r = .257; \quad t = .7; \]

\[
\text{Solve}[x^3 - (2 + r) x^2 + (2 r + t^2 + 1) x - r = 0, \; x] \\
\{\{x \to 0.15274\}, \{x \to 1.05213 - 0.758695 i\}, \{x \to 1.05213 + 0.758695 i\}\}
\]

The real solution gives the widely accepted value of \( R = 0.15 \).
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