Chapter 4

All-Optical Switching in Chlorophyll-A with CW Pump Beam Excitation

4.1 Introduction

In this Chapter, a detailed analysis of all-optical light modulation with Chl-A based on nonlinear intensity-induced ESA, using the pump-probe technique has been presented. The transmission characteristics of a weak cw probe beam at different wavelengths through Chl-A switched by a cw pump beam at 672 nm that corresponds to the peak absorption wavelength of ground $S_0$-state have been analyzed in detail. The rate equation approach is used to analyze the modulation characteristics of Chl-A by incorporating the pump beam propagation effect in the theoretical model.

Since a wide range of Chlorophylls and its variants exist in nature, and as the spectral and kinetic properties of Chl-A can be modified by a number of biotechnological techniques, the effect of various parameters such as probe wavelength, normalized parameter $\beta_m (\sigma_{S0}NL)$ and lifetimes of various states has also been analyzed in detail. It is shown that there exists an optimum value of $\beta_m$ for maximum modulation, for the case when the ground state also absorbs the probe beam. Further, the results have been used to design all-optical SLMs, switches and logic gates including AND, OR, NOT, NAND and NOR logic gates. The results have also been shown to be useful in parallel computing.

4.2 Theoretical Model

The light-induced population changes in different energy levels can be described by the rate equations in terms of the photo-induced and thermal transitions of different levels as [Reddy (1991), Speiser and Orenstein (1988), Speiser et al. (1989), Roy et al. (2000), Singh and Roy (2002), Singh et al. (2003)
Roy et al. (2001), Sharma and Roy (2004)],

\[
\frac{dN_{S0}}{dt} = -\sigma_{S0} I_m(x) N_{S0} + \frac{N_{SI}}{\tau_{S0}} + \frac{N_{TI}}{\tau_{T0}} \tag{4.1}
\]

\[
\frac{dN_{SI}}{dt} = \sigma_{S0} I_m(x) N_{S0} - \frac{N_{SI}}{\tau_{S0}} - \frac{N_{SI}}{\tau_{ST}} \tag{4.2}
\]

\[
\frac{dN_{TI}}{dt} = \frac{N_{SI}}{\tau_{ST}} - \frac{N_{TI}}{\tau_{T0}} \tag{4.3}
\]

where \(N_{S0}, N_{SI}\) and \(N_{TI}\) are the population densities of \(S_0, S_1\) and \(T_1\) states, respectively; \(\sigma_{S0}\) is the absorption cross section of \(S_0\) state at probe beam wavelength; and \(\tau_{S0}, \tau_{T0}\) and \(\tau_{ST}\) are the relaxation times for the non-radiative transitions \(S_1 \rightarrow S_0, T_1 \rightarrow S_0,\) and \(S_1 \rightarrow T_1,\) respectively. In the present analysis, we have neglected the relaxation from the higher energy states \(S_2\) and \(T_2\) as they are very fast (\(-\text{ps}\)) and hence can be considered to be almost instantaneous [Correa et al. (2002), Linschitz and Sarkanen (1958)]. \(I_m'(x)\) is the photon density flux of the modulating pump laser beam (ratio of intensity \(I_m'(x),\) to the photon energy \(h\nu\)) and \(x\) is the sample thickness. Assuming a cw or quasi-cw laser beam with broad light pulses, the light-induced population densities in the various levels at steady-state are given by

\[
N_i = N_{S0} (\tau_{S0}^{-1} + \tau_{ST}^{-1})^{-1} I_m(x) \left( \frac{I_m'(x) (\tau_{S0}^{-1} + \tau_{ST}^{-1})}{\tau_{S0} \tau_{ST}^{-1}} \right) \tag{4.4}
\]

where, \(N_i, i = S_0, S_1\) and \(T_1\) are the population densities of the respective states,

\[
N_{S0} = N/X \tag{4.5}
\]

with

\[
X = \left[1 + k I_m(x) \right] \tag{4.6}
\]

\[
k = \sigma_{S0} \left( \tau_{S0}^{-1} + \tau_{ST}^{-1} \right)^{-1} \left( 1 + \tau_{T0} \tau_{ST} \right) \tag{4.7}
\]

and

\[
N = N_{S0} + N_{SI} + N_{TI} \tag{4.8}
\]

is the total number of active molecules.
4.2.1 Propagation of the Modulating Pump Beam

For strongly absorbing and thick media, the modulating pump beam is absorbed as it propagates through the nonlinear medium. Hence, it becomes necessary to consider its propagation effect. The propagation of pump beam through the medium, in general, is governed by the equation [Speiser and Orenstein (1988), Speiser et al. (1989)]

\[
\frac{dI_m'(x)}{dx} = -\alpha_m I_m'(x)
\]

(4.9)

where \(x\) is the distance in the medium and the nonlinear absorption coefficient for the pump beam \((\alpha_m)\), in general, is defined as

\[
\alpha_m(x) = \sigma_{s0} N_{s0}(x) + \sigma_{s1} N_{s1}(x) + \sigma_{t1} N_{t1}(x)
\]

(4.10)

Assuming that the absorption cross-sections of \(S_1\) and \(T_1\) states of Chl-A at pump beam wavelength at 672 nm are very small and can be neglected, the absorption coefficient for modulating pump beam can be written as,

\[
\alpha_m(x) = \sigma_{s0} N_{s0}(x)
\]

The expression for the normalized transmitted modulating pump beam intensity (NTMI) can be obtained by integrating Eq. (4.9) for propagation over a length \(L\) in the medium, which yields,

\[
\frac{I_{\text{mout}}}{I_{\text{min}}} = \exp \left[ -\beta_m + k I_{\text{min}} \left( 1 - \frac{I_{\text{mout}}}{I_{\text{min}}} \right) \right]
\]

(4.11)

where \(I_{\text{min}}\) is the intensity of input pump beam at \(x = 0\), \(I_{\text{mout}}\) is the intensity of pump beam after propagating a distance \(x = L\) in the medium, and \(\beta_m = \sigma_{s0} NL\), a normalized parameter.

The solution of Eq. (4.11) can be written as,

\[
\frac{I_{\text{mout}}}{I_{\text{min}}} = \frac{1}{k I_{\text{min}}} W(p)
\]

(4.12)

where \(W(p)\) is the Lambert's function, defined as the multivalued inverse of the function \(p \exp(p)\), where \(p = k I_{\text{min}} \exp(-\beta_m + k I_{\text{min}})\) [Cranmer (2004)]. Equivalently, the multiple branches of \(W(p)\) are the multiple roots of \(W(p) \exp(W(p)) = p\).
4.2.2 Propagation of the Probe Beam

The SLM performance is determined by the propagation of the probe laser beam through a nonlinear medium. The intensity of the probe laser beam $I_p(x)$ for $I_p << I_m$ is given by

$$\frac{dI_p(x)}{dx} = -\alpha_p I_p(x)$$  \hspace{1cm} (4.13)

where the absorption coefficient at probe beam wavelength ($\alpha_p$), in general, is defined as

$$\alpha_p(x) = \sigma_{Sp} N_{Sp}(x) + \sigma_{Sp} N_{St}(x) + \sigma_{Sp} N_{Te}(x)$$ \hspace{1cm} (4.14)

The transmission of the probe beam can be obtained explicitly from Eqs. (4.9) and (4.13), from which we get [Speiser and Orenstein (1988), Speiser et al. (1989)]

$$\frac{dI_p(x)}{I_p(x)} = \left(\frac{\alpha_p}{\alpha_m}\right) \frac{dI_m(x)}{I_m(x)}$$ \hspace{1cm} (4.15)

Eq. (4.15) can be integrated to yield the normalized transmitted probe beam intensity (NTPI) as,

$$\frac{I_{pout}}{I_{pin}} = \left(\frac{I_{mou}}{I_{min}}\right)^\kappa \exp\left[\xi I_{min} \left(\frac{I_{mou}}{I_{min}} - 1\right)\right]$$ \hspace{1cm} (4.16)

where

$$\kappa = \frac{\sigma_{Sp}}{\sigma_{Sm}}$$ \hspace{1cm} (4.17)

and

$$\xi = \tau_{Sp} \left(\sigma_{Sp} \tau_{St} + \sigma_{Sp} \tau_{Te}\right) \left(\tau_{Sp} + \tau_{St}\right)$$ \hspace{1cm} (4.18)

Eq. (4.16) expresses the transmission of the probe beam taking into account the propagation effect of pump beam.

The NTPI without considering pump beam propagation effect can be written as [Roy et al. (2000)]

$$\frac{I_{pout}}{I_{pin}} = \exp\left[-\frac{\beta_m}{X} \left(\xi I_{min} + \kappa\right)\right]$$ \hspace{1cm} (4.19)

As mentioned in chapter 2, dynamic range, a typical property of a SLM, can be defined as the ratio of NTPI through a sample of length $L$ in the presence of the
pump beam, to that in the absence of the pump beam as given in the following expression [Speiser and Orenstein (1988), Speiser et al. (1989), Roy et al. (2000)]

\[
\delta = \frac{\left( \frac{I_{\text{pout}}}{I_{\text{pin}}} \right)_{I'_{\text{min}}}}{\left( \frac{I_{\text{pout}}}{I_{\text{pin}}} \right)_{I'_{\text{min}}=0}}
\]

(4.20)

and the sensitivity, which is defined as [Speiser and Orenstein (1988), Speiser et al. (1989), Roy et al. (2000)]

\[
S = -\left( \ln \delta \right)/I'_{\text{min}}
\]

(4.21)

4.3 Results and Discussion

The transmission characteristics of pump and probe beam, namely the normalized transmitted modulating pump intensity (NTMI) and normalized transmitted probe intensity (NTPI) with input modulating pump intensity \( I'_{\text{min}} \), have been obtained by computer simulations using Eqs. (4.1) - (4.19), for typical parameters given in Table 4.1 and sample thickness \( L = 2 \text{ mm} \).

Variation in NTMI at 672 nm with \( I_{\text{min}} \), for different values of \( \beta_m \) is shown in Fig. 4.1. It is evident from Fig. 4.1 that initially, NTMI is lower at lower values of \( I'_{\text{min}} \) and increases with increase in \( I'_{\text{min}} \). This can be explained by the variation in normalized population densities of various states with \( I'_{\text{min}} \) as shown in Fig. 4.2. Initially, in the absence of \( I'_{\text{min}} \), population of the ground state is maximum. As \( I'_{\text{min}} \)

Table 4.1 Lifetimes and absorption cross-sections of the different states [Correa et al. (2002), Linschitz and Sarkanen (1958), Baugher et al. (1979)].

<table>
<thead>
<tr>
<th>Life time (s)</th>
<th>Absorption cross-section</th>
<th>Values (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>410 nm</td>
</tr>
<tr>
<td>( \tau_{50} ) 6.2 \times 10^{-9}</td>
<td>( \sigma_{50} )</td>
<td>1.5 \times 10^{-16}</td>
</tr>
<tr>
<td>( \tau_{ST} ) 1.5 \times 10^{-9}</td>
<td>( \sigma_{91} )</td>
<td>1.91 \times 10^{-16}</td>
</tr>
<tr>
<td>( \tau_{TO} ) 1.0 \times 10^{-7}</td>
<td>( \sigma_{11} )</td>
<td>3.4 \times 10^{-17}</td>
</tr>
</tbody>
</table>
increases, the normalized population density of the S₀ state decreases which results in lower absorption of the pump beam and increase in NTMI. The population of the T₁-state increases with increase in $I'_{\text{min}}$. There is no appreciable change in the population of S₁ state due to very fast transition from S₁ → S₀ and S₁ → T₁ state.

![Graph](image1)

**Fig. 4.1** Variation of NTMI at 672 nm with $I'_{\text{min}}$ at 672 nm for different values of $\beta_m$.

![Graph](image2)

**Fig. 4.2** Variation of the normalized population densities of various states of Chl-A with $I'_{\text{min}}$ at 672 nm.
Figure 4.3 shows the variation of NTPI at 476 nm with $I'_{\text{min}}$ at 672 nm, for different values of $\beta_m$. As evident, the effect of pump beam propagation is more at higher values of $\beta_m$ and lower values of $I'_{\text{min}}$. As expected, the percentage modulation considering the propagation effect of the pump beam is less due to decrease in the effective pump beam intensity. From Fig. 4.3, the probe beam is modulated by 91.3 %, even after considering the pump beam propagation effect, for $I'_{\text{min}} = 100 \text{ kW/cm}^2$ at 672 nm and $\beta_m = 5$. The corresponding values of $\delta$ and $S$ are 0.871 and $1.38 \times 10^{-5}$ cm$^2$/W, respectively. For this case, the probe beam can be completely switched off (i.e. 100% modulation) for $I'_{\text{min}} = 100 \text{ kW/cm}^2$ and $\beta_m = 13$.

To quantify the effect of pump beam propagation, the variation of the difference in NTPI ($\Delta$NTPI) i.e. NTPI (with pump beam propagation effect) - NTPI (without pump beam propagation effect) with $I'_{\text{min}}$, for different values of $\beta$ is shown in Fig. 4.4. For a given $\beta_m$, $\Delta$NTPI is maximum at a particular value of $I'_{\text{min}}$. 
This is due to the fact that initially, when \( I_{\text{min}}' = 0 \), \( \Delta \text{NTPI} \) is zero. On increasing \( I_{\text{min}}' \), \( \Delta \text{NTPI} \) increases due to increased absorption by the \( T_1 \)-state. At higher values of \( I_{\text{min}}' \), saturation of absorption results in \( \Delta \text{NTPI} \) becoming zero.

![Graph showing variation in NTPI at 476 nm with different values of \( \beta_m \).](image)

**Fig. 4.4** Variation in difference in NTPI with propagation effect and without propagation effect with \( I_{\text{min}}' \) for different values of \( \beta_m \).

The variation of NTPI at 532 nm with \( I_{\text{min}}' \) at 672 nm, for different values of \( \beta_m \), is shown in Fig. 4.5 (a). For this case, \( \sigma_{\text{Sop}} \neq 0 \) results in lower NTPI in the absence of \( I_{\text{min}}' \). As \( I_{\text{min}}' \) increases, the NTPI decreases due to increase in the population of excited states. For example, for \( \beta_m = 1, 3, 5, 7, 9 \) and 11, percentage modulation of the probe beam is 29.6%, 60.7%, 72.4%, 75.5%, 74.7% and 72.1%, respectively, for \( I_{\text{min}}' = 100 \text{ kW/cm}^2 \). An optimum value of \( \beta_m \) is obtained for this case, for which percentage modulation is maximum. Variation in percentage modulation of the probe beam at 532 nm with \( \beta_m \) for different values of \( I_{\text{min}}' \), is shown in Fig. 4.5 (b), which shows that percentage modulation of probe beam increases initially with increase in \( \beta_m \) and after a certain value, it decreases resulting in an optimum value of \( \beta_m \). For instance, for \( I_{\text{min}}' = 50 \text{ kW/cm}^2 \) and \( I_{\text{min}}' = 100 \text{ kW/cm}^2 \), the optimum value of \( \beta_m \) is 6.4 with 66.6% switching contrast and
7.4 with 75.5% switching contrast, respectively. The present results show that optimum $\beta_m$ increases as $I_{min}'$ increases.

![Graph](image)

Fig. 4.5 (a) Variation of NTPI at 532 nm with $I_{min}'$ at 672 nm, for different values of $\beta_m$. (b) Variation of switching contrast of the probe beam at 532 nm, in terms of percentage modulation with $\beta_m$, for different values of $I_{min}'$ at 672 nm.

The nature of modulation characteristics of the probe beam is reversed for probe beam at 410 nm. Figure 4.6 (a) shows the variation of NTPI at 410 nm for different values of $\beta_m$. Initially, in the absence of $I_{min}'$, the probe beam is absorbed by $S_0$-state, leading to lower linear transmission. As the molecules get excited by the pump beam, the ground state gets depleted. Also, absorption by the $S_1$ state is more than other states at 410 nm and its life time is short. Hence, these factors lead to an increase in NTPI as $I_{min}'$ increases. Solid and dashed lines show the variation
of NTPI at 410 nm with \( I'_{\text{min}} \) with and without pump beam propagation effect, respectively.

Fig. 4.6 (a) Variation of NTPI at 410 nm with \( I'_{\text{min}} \) at 672 nm, for different values of \( \beta_m \).

(b) Variation of switching contrast of the probe beam at 410 nm, in terms of percentage modulation with \( \beta_m \), for different values of \( I'_{\text{min}} \) at 672 nm.

Initially, in the absence of \( I'_{\text{min}} \), the NTPI is same for both cases. As \( I'_{\text{min}} \) increases, NTPI without propagation effect increases rapidly in comparison to with propagation effect, due to faster depletion of the ground state and finally both become equal with further increase in \( I'_{\text{min}} \). In this case also, an optimum value of \( \beta_m \) has been obtained for maximum percentage modulation. Variation of NTPI at
410 nm in terms of percentage modulation with $\beta_m$, for different values of $I'_{\text{min}}$, is shown in Fig. 4.6 (b). It is evident that initially switching contrast increases with increase in $\beta_m$ and after a certain value, it starts to decrease, which results in an optimum value of $\beta_m$. For instance, for $I'_{\text{min}} = 50 \text{ kW/cm}^2$ and 100 kW/cm$^2$, optimum value of $\beta_m$ is 2.9 with 25.8% switching contrast and 3.6 with 32.9% switching contrast, respectively.

A large variety of chlorophylls are found in nature. The kinetic and spectral properties of chlorophylls vary with different forms and can also be altered by various physical, chemical and biotechnological techniques [Vernon and Seely (1966), Linschitz and Sarkanen (1958), Tkachenko et al. (1992), Bonnett et al. (1994)]. Variation of NTPI at 672 nm with $I'_{\text{min}}$ for different values of singlet-state lifetime $\tau_S$, is shown in Fig. 4.7. It is evident from Fig. 4.7 that as $\tau_S$ increases, NTPI decreases due to increase in the population of triplet state, resulting in more absorption of the probe beam.

Figure 4.8 shows the variation of NTPI at 672 nm with $I'_{\text{min}}$ for different values of triplet state lifetime $\tau_T$. The NTPI decreases with $I'_{\text{min}}$ and also decreases
as $\tau_{T0}$ increases, due to slower depopulation rate of $T_1$-state. Inset shows the corresponding variation for different values of intersystem crossing time $\tau_{ST}$. NTPI decreases as $\tau_{ST}$ decreases, resulting in higher percentage modulation of the probe beam.

![Graph showing variation of NTPI at 476 nm with $I_{min}$ at 672 nm for different values of triplet-state lifetime $\tau_{T0}$, for $\beta_m = 7$. Inset shows the corresponding variation for different values of inter-system crossing time $\tau_{ST}$.](image)

Fig. 4.8 Variation of NTPI at 476 nm with $I_{min}$ at 672 nm, for different values of triplet-state lifetime $\tau_{T0}$, for $\beta_m = 7$. Inset shows the corresponding variation for different values of inter-system crossing time $\tau_{ST}$.

Variation in NTPI at 410 nm with $I_{min}$ for different values of $\tau_{T0}$ is shown in Fig. 4.9, for $\beta_m = 1$. As $\tau_{T0}$ increases, slower depopulation of $T_1$ state results in decrease in the population of $S_0$ and $S_1$ state. Since, NTPI characteristics at 410 nm are based on $S_1$-state dynamics due to the higher absorption cross-section of $S_1$-state than $S_0$ and $T_1$ state. Therefore, NTPI at 410 nm increases as $\tau_{T0}$ increases due to decrease in the population of $S_1$-state.
Fig. 4.9 Variation of NTPI at 410 nm with $I'_\text{min}$ at 672 nm, for different values of $\tau_{70}$, for $\beta_m = 7$.

Fig. 4.10 Variation of NTPI at 410 nm with $I'_\text{min}$ at 672 nm, for different values of $\tau_{50}$, for $\beta_m = 7$. Inset shows the corresponding variation for different values of $\tau_{50}$.

Effect of $\tau_{50}$ on NTPI characteristics at 410 nm with $I'_\text{min}$ is shown in Fig. 4.10. The population of the S1-state decreases as $\tau_{50}$ increases due to faster intersystem crossing time, resulting in an increase in the NTPI. Inset of Fig. 4.10
shows the variation of NTPI at 410 nm with $I'_{\text{min}}$ for different values of $\tau_{\text{ST}}$. As $\tau_{\text{ST}}$ increases, NTPI decreases due to increase in the population of the S$_1$-state.

4.4 Application of Results

4.4.1 Design of All-optical Spatial Light Modulator

The modulation characteristics of a weak cw probe beam for Chlorophyll-A have been used to design an all-optical SLM. Typical SLM properties i.e. dynamic range $\delta$ and sensitivity $S$ have been estimated. For probe (read) beam at 476 nm, absorption cross-section of the S$_0$-state $\sigma_{S0p} = 0$, which corresponds to the ideal case [Roy et al. (2000)]. Therefore, variation of dynamic range with $I'_{\text{min}}$ at 672 nm for different values of $\beta_m$ will be same as the variation of NTPI at 476 nm, as shown in Fig. 4.3. Estimated values of $\delta$ and $S$ are 0.871 and $1.38 \times 10^{-5}$ cm$^2$/W, respectively, at $I'_{\text{min}} = 50$ kW/cm$^2$ at 672 nm, for $\beta_m = 5$. Variation of dynamic range for a probe beam at 532 nm with input pump intensity $I'_{\text{min}}$ at 672 nm is shown in Fig. 4.11. For this case, $\delta = 0.18$ and $S = 1.74 \times 10^{-5}$ cm$^2$/W at $I'_{\text{min}} = 100$ kW/cm$^2$ at 672 nm, for $\beta_m = 5$.

![Fig. 4.10](image_url)  
*Fig. 4.10 Variation of dynamic range at 532 nm with $I'_{\text{min}}$ at 672 nm, for different values of $\beta_m$.\*
4.4.2 Design of All-Optical Logic Gates

The transmission characteristics of probe beam at 410 nm can be used to design two input all-optical OR and AND logic gates by considering the NTPI as output and $I'_{\text{min}}$ as combination of two inputs, as shown in Fig. 4.11 (a), for $\beta_m = 7$. All-optical AND logic operation can be obtained by considering two input intensities $I'_{\text{min1}} = I'_{\text{min2}} = 20 \text{ kW/cm}^2$ and a threshold at 0.1. The NTPI becomes low when either one or none of the input beams is present and becomes high when both the input beams are present. All-optical OR logic gate can be designed by considering two input intensities $I'_{\text{min1}} = I'_{\text{min2}} = 40 \text{ kW/cm}^2$. The NTPI becomes low when none of the input beams is present and becomes high when one or both the input beams are present.

The same setup can be used to design all-optical NOT and the two input universal NOR and NAND logic gates by considering the NTPI at 476 nm as output and $I'_{\text{min}}$ as combination of input pump beams. The switching of the transmission characteristics from high (above threshold) to low (below threshold) at lower and higher input $I'_{\text{min}}$ values, respectively, correspond to the all-optical NOT logic gate as is evident from Fig. 4.11 (b).

All-optical NAND logic operation can be obtained by considering two input intensities $I'_{\text{min1}} = I'_{\text{min2}} = 20 \text{ kW/cm}^2$ and a threshold at 0.25. The NTPI becomes high when either one or none of the input beams is present and becomes low when both the input beams are present. All-optical NOR logic gate can be designed by considering two input intensities $I'_{\text{min1}} = I'_{\text{min2}} = 40 \text{ kW/cm}^2$. The NTPI becomes low when either one or both the input beams are present and becomes high when none of the input beams is present. High modulation rates can be achieved with Chl-A, as the transitions are $\sim \mu$s. The proposed design shows only the applicability of the SLM characteristics for generating single level optical logic. The implementation for next or higher level logic requires further investigation.
Fig. 4.11 Variation of NTPI at 410 nm in Chl-A with pump laser beam intensity at 672 nm and realization of two input all-optical logic gates for case (ii): (a) OR and AND logic gates by considering a common threshold level at 0.1, (b) NOT and the universal NOR and NAND logic gates, by considering a common threshold level at 0.25. Vertical and horizontal dotted lines indicate input and output values for respective logic gates. Horizontal dashed line shows the threshold level.

The above proposed designs would be useful to obtain the various logic operations simultaneously in parallel for higher-order computing circuits as shown in Fig. 4.12 (a). The logic gates as shown in Fig. 4.11, can be realized in parallel by the schematic setup as explicitly shown in Fig. 4.12 (b) with input intensities $I'_\text{min}_1$ and $I'_\text{min}_2$ made to be collinearly incident on Chl-A sample with corresponding weak cw probe beam. Different logic gates can be simultaneously realized using suitable beam splitters for incident pump and probe beams.
The present study demonstrates the feasibility of using Chl-A for all-optical device applications. Since, the kinetic and spectral properties of Chl-A can also be tailored by physical, chemical and biotechnological techniques, the transmission characteristics can be optimized to increase the contrast between the logical high and low states.

4.5 Conclusion

A theoretically analysis of all-optical light modulation with Chl-A based on intensity induced excited-state absorption has been presented. The transmission of a weak cw probe beam at different wavelengths i.e. 476, 532 and 410 nm is switched by a cw modulating pump laser beam at 672 nm. Propagation effect of pump beam
has also been incorporated in the analysis. It has been shown that the modulation characteristics can be reversed for probe beam at 410 nm. It has also been shown that the probe beam can be completely switched off (i.e. 100% modulation) for probe beam at 476 nm. The effect of various parameters such as normalized parameter $\beta_m$ and lifetimes of different states on the modulation characteristics has also been analyzed in detail. An optimum value of $\beta_m$ has also been obtained for probe beam at 532 nm and 410 nm, due to $\sigma_{\text{SOP}} \neq 0$.

The results have been used to design all-optical SLM, switches and logic gates including AND, OR, NOT, NAND and NOR logic gates that are the basic building blocks of information processing computing devices. The results have also been shown to be useful in parallel computing where one can design all-optical logic gates using a single sample of Chl-A, only by changing the probe beam wavelength and threshold level.