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ANALYSIS AND DESIGN OF ALL-OPTICAL SWITCHING IN APODIZED AND CHIRPED BRAGG GRATINGS

M. J. Moghimi and H. Ghafoori-Fard

Faculty of Electrical Engineering
Amirkabir University of Technology
Tehran, Iran

A. Rostami

Photonics and Nanocrystal Research Laboratory
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz 51664, Iran

Abstract—In this paper, effects of the different apodization and chirp functions in one-dimensional nonlinear Bragg grating on switching characteristics are studied. It is shown that with increasing the Gaussian width in the case of Gaussian apodization, slope of transfer function is increased. The situation is same in the case of raised cosine apodization function too. Also, in the case of quadratic apodization with decreasing the apodization parameter the slope of the transfer function is improved. Using the chirp different functions the switching threshold can be controlled. So, the presented structure as optical switch can be designed for optimum slope and threshold of switching using desired apodization and chirp functions. So, the presented material in this paper shows that there are possibilities for management of all-optical switching using suitable apodization and chirp functions.

1. INTRODUCTION

Dense wavelength division multiplexing (DWDM) has been widely used as a method of expanding the capacity of optical fiber networks. This type of optical communication technique needs some basic blocks with capabilities including multiplexing, demultiplexing, switching, routing monitoring and attenuation of each individual wavelength within the packet of wavelengths propagating through optical fiber network. These functions can be realized using passive components, which there are interesting and currently used for optical signal processing. In optical passive devices the Bragg gratings is widely used, discussed in literature and applied for optical signal processing tasks. Usually, these devices can be implemented using Bragg gratings. Nowadays, from our point of view, these functions are implemented separately (single function passive device) without efficient controllable and reconfigurable algorithm in electrical (electro-optical functional blocks) and optical domains (all-optical functional blocks). So, if optical devices can be integrated into electronically controllable geometry there will be a basis for the programmable optical functional devices. These types of devices really are new and useful for more development of optical processing and computing with flexible programming. So, there is basic interest for introducing and development of the mentioned devices and systems for realization of optical computing. In this paper we concentrate on optical switching devices made by Bragg gratings because of important role in optical communication.

Up to now, the switching burden in communication systems has been laid almost entirely on electronics. Electronic switching is a mature and sophisticated technology. That has been studied extensively. However, as the network capacity increases, electronic switching nodes seem unable to keep up [1–10]. Apart from that, electronic equipment is strongly dependent on data rate and protocol. If optical signals could switch without conversion to electrical form, both of these drawbacks would be eliminated. The transfer of the switching function from electronics to optics will result in a reduction in the network equipment, an increase in the switching speed, and thus network throughput, and a decrease in the operating power. One of the most important schemes for optical switch is nonlinear Bragg grating. For realization of Bragg grating electro-optic effect is usually used [6–13]. For doing the switching purpose we consider a Bragg grating system. The introduced system acts as an optical chip. The induced index of refractions by sampled electric potentials applied through metallic strips on electro-optic media. The proposed structure is simulated numerically using the Transfer Matrix Method (TMM). Apodized amplitude of refractive index with different window functions is used to optimize the parameters of the introduced optical switch. Other methods such as optical micro electromechanically systems (Optical MEMS) were used for optical switching [14–19]. In these papers different approaches were used. In [19, 20] the authors applied superimposed Bragg gratings to multi wavelength switching. In all of these published papers periodic nonlinear structures were used for optical switching and they didn't consider apodization and chirp of refractive index on switching characteristics. So, in this paper we consider this subject and investigate effects of the apodization and chirp of refractive index on optical switching performance. We show that using these factors there are two degree of freedom to manipulate the switching characteristics. Thus optimization in presence of these factors can be done effectively.

Organization of the paper is as follows.

In Section 2 mathematical background for modeling of the light propagation in apodized and chirped periodic media is presented. Simulation result and discussion is presented in Section 3. Finally the paper ends with a short conclusion.

2. MATHEMATICAL BACKGROUND

For optical switching the following proposal is considered. In this figure a thick substrate and a thin optical complex multilayer generally including different index of refraction and layer thickness is considered as an optical switch.

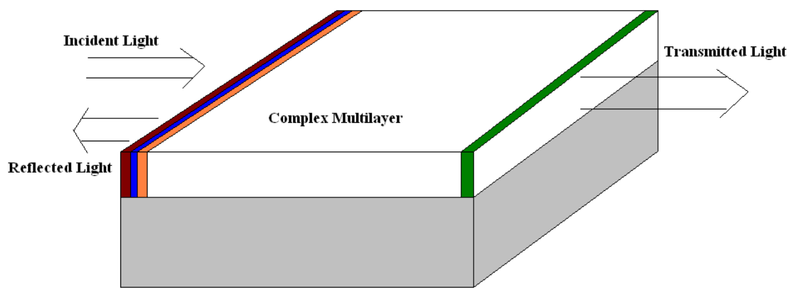

Figure 1. Schematic of the proposed optical switch.

For this structure the index of refraction generally can be explained as follows.

$$n(x)=n_{ave}+f(x)\left(\delta_l\sin(kx+\Phi(x))-\left|E^2\right|\delta_{nl}\sin(kx+\Phi(x))\right)\quad k=\frac{2\pi}{\Lambda}\tag{1}$$

where n_{ave}, δ_l, δ_{nl}, $\Lambda_i E$, $f(x)$ and $\Phi(x)$ are average index of refraction, amplitude of the index of refraction, amplitude of the nonlinear grating, period of grating, electric field, apodization function and chirp function respectively. Some of apodization and chirp functions are listed in Table 1.

Table 1. List of apodization functions.

Apodization/Chirp Function	**Equation**
Gaussian	$A(z) = e^{-a\left(\frac{z-0.5L}{L}\right)^2}$
Raised-cosine	$A(z) = 0.5\left(1+\cos\left(\pi\left(\frac{z-0.5L}{a}\right)\right)\right)$
Quadratic	$A(z) = \left(1-\frac{T}{12}+T\left(\frac{z-0.5L}{L}\right)^2\right)$
Linear chirp function	$A(z) = \frac{2F(z-0.5L)}{L^2}$

To analyze this structure, we divided it into N sections. Each section is considered homogenous. The approximated multilayer dielectric structure is described by

$$n(x) = \begin{cases} n_0 & x < x_0 \\ n_1 & x_0 < x < x_1 \\ n_2 & x_1 < x < x_2 \\ \vdots & \\ n_N & x_{N-1} < x < x_N \\ n_s & x_N < x \end{cases}, \tag{2}$$

where n_l, x_l, n_s and n_0 are the refractive index of lth layer, the position of the interface between the lth layer and the $(l+1)$th layer, the substrate index of refraction and the incident medium refractive index respectively. The layer thickness d_i is L/N where L is the length of the grating.

$$d_i = \frac{L}{N}, \quad i = 1, 2, 3, \ldots, N \tag{3}$$

The electric field of a general plane-wave solution of the wave equation can be written as:

$$E = E(x)e^{i(\omega t-\beta z)}, \tag{4}$$

where the electric field distribution $E(x)$ can be written as:

$$E(x) = \begin{cases} A_0 e^{-ik_{0x}(x-x_0)} + B_0 e^{ik_{0x}(x-x_0)} & x < x_0 \\ A_l e^{-ik_{lx}(x-x_l)} + B_l e^{ik_{lx}(x-x_l)} & x_{l-1} < x < x_l \\ A_s e^{-ik_{sx}(x-x_N)} + B_s e^{ik_{sx}(x-x_N)} & x_N < x \end{cases}, \tag{5}$$

where k_{lx} is the x component of wave vector

$$k_{lx} = \left[\left(\frac{n_l \omega}{c} \right)^2 - \beta^2 \right]^{\frac{1}{2}}, \tag{6}$$

and is related to the ray angle θ_l by:

$$k_{lx} = n_l \frac{\omega}{c} \cos(\theta_l) = \frac{2\pi}{\lambda} \cos(\theta_l) \tag{7}$$

The electric field $E(x)$ consists of right and left traveling waves and can be defined as follows.

$$E_l(x) = \mathrm{Re}^{-ik_l x} + Le^{ik_l x} = A_l(x) + B_l(x), \tag{8}$$

where $\pm k_l x$, R and L are constants in homogenous layer respectively. $E(x)$ is a continuous function of x. If we represent two amplitudes of $E(x)$ as column vectors, the column vectors are related by:

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = D_0^{-1} D_l \begin{pmatrix} A_l \\ B_l \end{pmatrix} \tag{9}$$

$$\begin{pmatrix} A_l \\ B_l \end{pmatrix} = P_l D_l^{-1} D_{l+1} \begin{pmatrix} A_{l+1} \\ B_{l+1} \end{pmatrix}, \tag{10}$$

where A_l, B_l and D_l represent the amplitude of plane waves at interface $x = x_l$ and dynamical matrix respectively described by:

$$D_\alpha = \begin{pmatrix} 1 & 1 \\ n_\alpha \cos\theta_\alpha & -n_\alpha \cos\theta_\alpha \end{pmatrix}, \quad \alpha = 0, l, l+1 \tag{11}$$

where θ_α and P_l are the ray angle in each layer and propagation matrix respectively and defined by:

$$P_l = \begin{pmatrix} e^{i\phi_l} & 0 \\ 0 & e^{-i\phi_l} \end{pmatrix} \tag{12}$$

$$\phi_l = k_{lx} \cdot d_l \tag{13}$$

The relation between A_0, B_0 and A_s, B_s (or A_{N+1}, B_{N+1}) can be determined by:

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} A_s \\ B_s \end{pmatrix} \tag{14}$$

With the matrix given by:

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1} \left[\prod_{i=1}^{N} D_i P_i D_i^{-1} \right] D_s \tag{15}$$

This approach named Transfer Matrix Method (TMM). If the light is

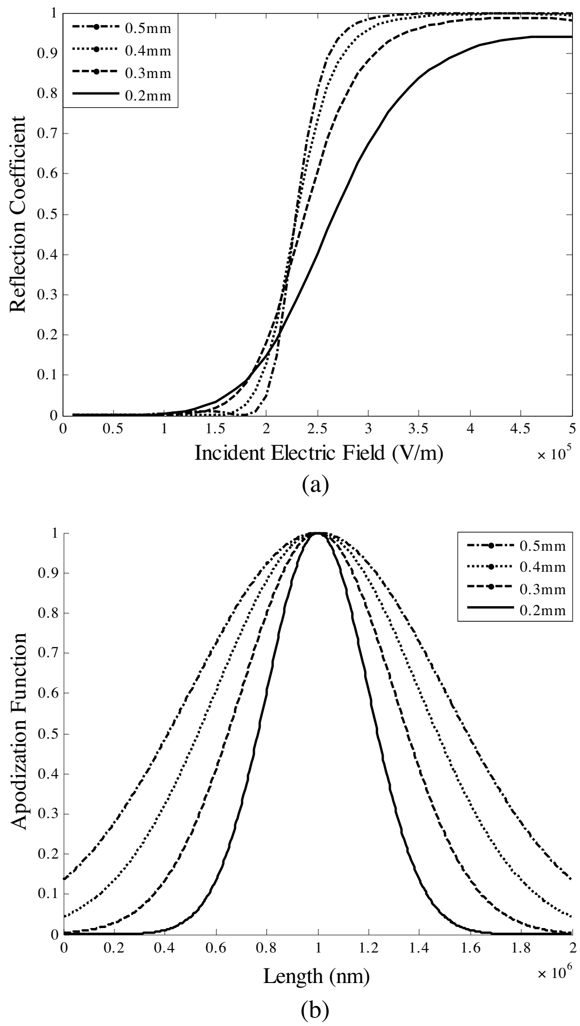

Figure 2. (a) The reflection coefficient vs. incident electric field amplitude, (b) the apodization function (for Gaussian apodization function with different sigma).

incident from medium 0, the reflection coefficient is defined as:

$$r(\lambda) = \left(\frac{B_0}{A_0}\right)_{B_s=0} \tag{16}$$

Similarly, the transmission coefficient is:

$$t(\lambda) = \left(\frac{A_s}{A_0}\right)_{B_s=0} \tag{17}$$

Using matrix Equation (14) and definitions (15), (16), we obtain:

$$r(\lambda) = \frac{M_{21}}{M_{11}} \tag{18}$$

and

$$t(\lambda) = \frac{1}{M_{11}} \tag{19}$$

Reflectance is given by:

$$R(\lambda) = |r(\lambda)|^2 = \left|\frac{M_{21}}{M_{11}}\right|^2 \tag{20}$$

Provided medium 0 is lossless.

3. SIMULATION RESULTS AND DISCUSSION

In this section simulated results for the proposed structure are illustrated and discussed. In the following first we consider effects of different apodization functions on switching characteristics and then we study effect of the chirp function.

3.1. Gaussian Apodization Function

In this case the Gaussian apodization profile is assumed as follows.

$$A(z) = e^{\left[-a\left(\frac{z-0.5L}{L}\right)^2\right]}, \tag{21}$$

where a is the Gaussian width. For this apodization function and given constant the reflection coefficient and functions are shown in Fig. 2.

In Table 2, slope of the transfer function is presented versus the Gaussian width parameter. It is shown that with decreasing of the Gaussian width the slope of the transfer function is increased.

3.2. Raised-cosine Apodization Function

For this case the following apodization function is adopted.

$$A(z) = 0.5\left(1+\cos\left(\pi\left(\frac{z-0.5L}{a}\right)\right)\right), \tag{22}$$

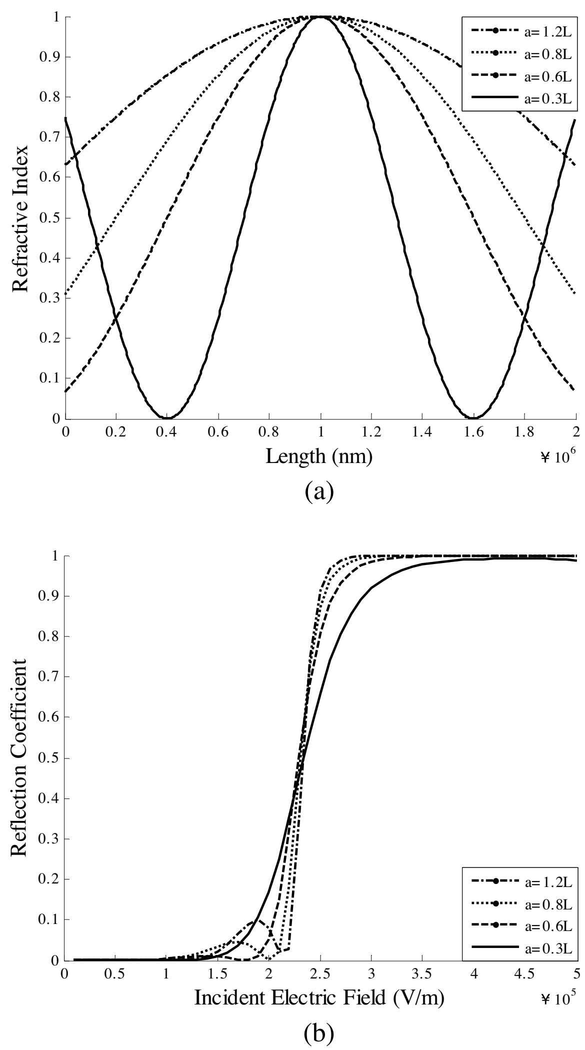

Figure 3. (a) Refractive index vs. grating length, and (b) the reflection coefficient vs. incident electric field.

Table 2. Transients for different Gaussian widths.

Gaussian width (mm)	Transient (10^5) V/m
0.5	1
0.4	2
0.3	2.8
0.2	3

For this apodization function the refractive index and reflection coefficient are illustrated in Fig. 3. It is shown that with increasing the parameter a, which is used in the apodization function, the slope of the transfer function is increased and transient region is decreased. So, using suitable value for this parameter an optimized operation for designed optical switch can be obtained. Table 3 shows some transient region duration for different values of the parameter.

Table 3. Transient duration for different parameters of raised cosine.

a (L)	Transient (10^5) V/m
1.2	0.3
0.8	0.6
0.6	1.1
0.3	2.2

3.3. Quadratic Apodization Function

For third case the quadratic apodization is considered. In this case the index of refraction apodization function is controlled using a parameter named T.

$$A(z) = \left(1 - \frac{T}{12} + T\left(\frac{z - 0.5L}{L}\right)^2\right), \tag{23}$$

According previous cases effect of quadratic apodization on switching parameters is considered and in Table 4 transient duration with increasing of the parameter T in apodization function is reported. It is observed that with decreasing the parameter the transient duration of the transfer function is decreased.

Figure 4 shows variation of the transfer function with changing T. Also, in part (b) the apodization function versus the grating length is illustrated. Effect of the parameter (T) appeared in apodization function on switching performance is illustrated. It is observed that with small apodization parameter the switching quality is increased.

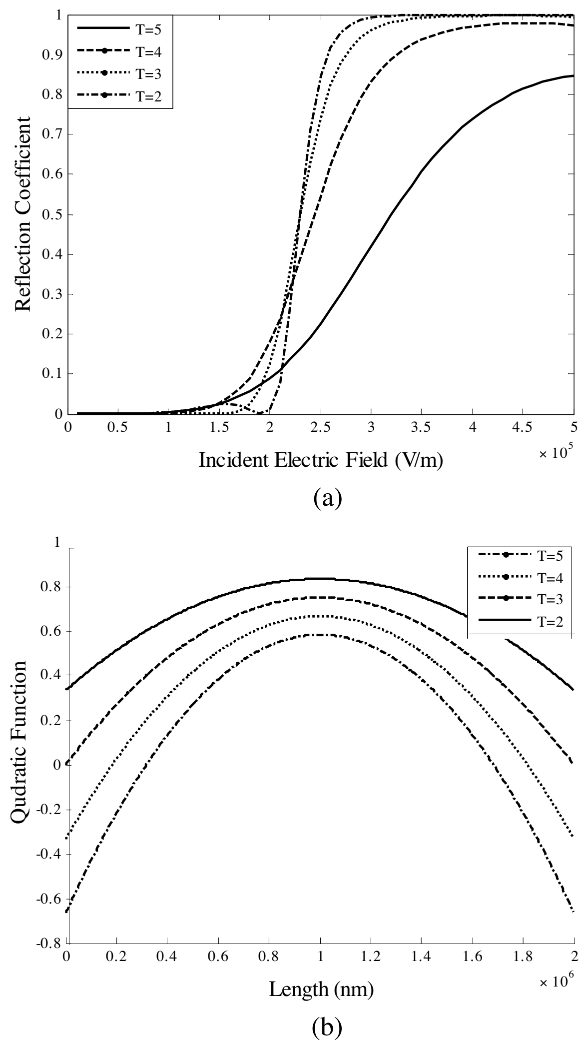

Figure 4. (a) The reflection coefficient vs. incident electric field and (b) Quadratic apodization function vs. grating length.

3.4. Linear Chirp Function

For investigation of the switching performance as a final study, the chirped refractive index is considered. For this purpose the following linear chirp function for modification of the refractive index is adopted.

$$A(z) = \frac{2F\,(z - 0.5L)}{L^2}, \tag{24}$$

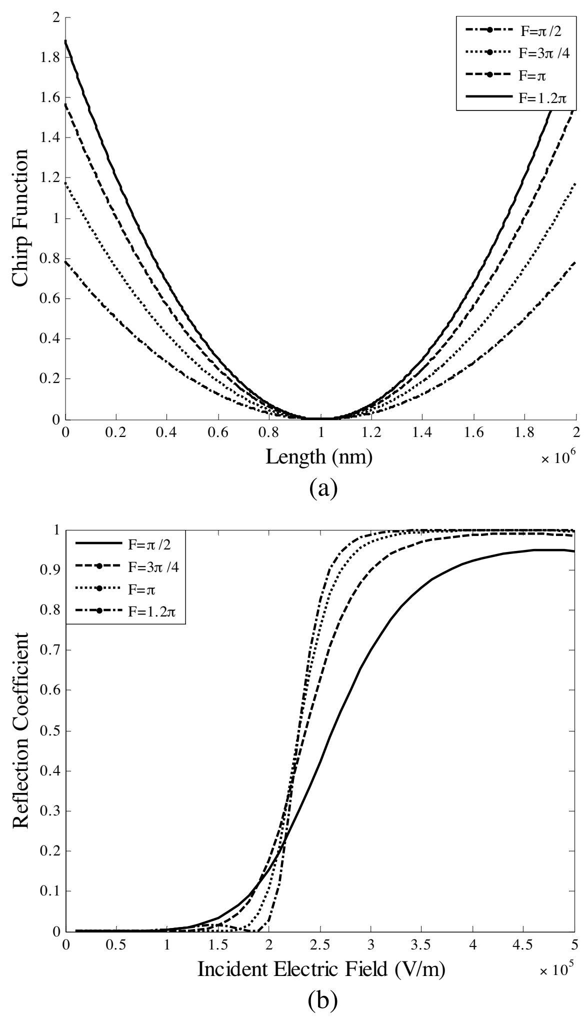

Figure 5. (a) Chirp function vs. grating length and (b) the reflection coefficient vs. incident electric field.

where F is chirp parameter.

The proposed switch with chirp function is studied numerically and the simulated result is illustrated in Fig. 5. Also, numerical data is given in Table 5 too. It is shown that with increasing the chirp parameter the transient duration is decreased. The tunable transfer function using the chirp parameter is illustrated in this figure.

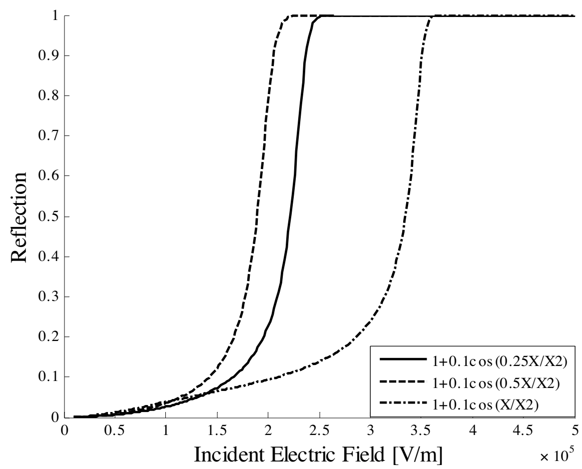

Figure 6. The reflection coefficient vs. incident electric field.

Effects of the other chirp function on switching performance are illustrated in the following figures. In Fig. 6 effect of cosine chirp function on performance of the proposed optical switch is investigated. It is observed that with increasing the spatial frequency of the chirp function the switching threshold is increased.

Table 4. Transient duration for different parameters of quadratic apodization.

Quadratic apodization function parameter (T)	Transient (10^5) V/m
2	1
3	1.8
4	2.5
5	4

Table 5. Transient duration of the transfer function.

Chirp Function Parameter (F)	Transient (10^5) V/m
$\pi/2$	3.5
$3\pi/4$	2.7
π	1.7
1.2π	1.2

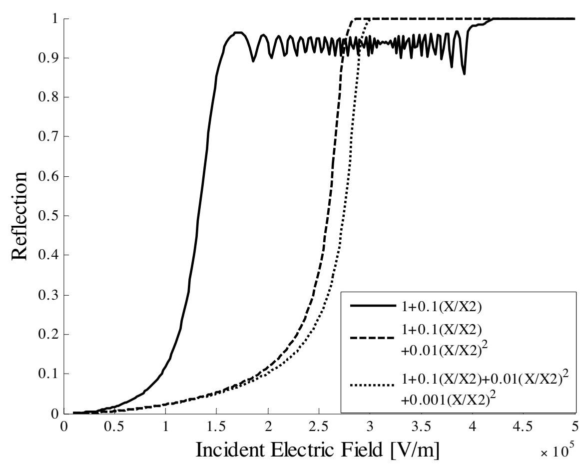

Figure 7. The reflection coefficient vs. incident electric field.

Also, considering effect of the power law chirp function on switching performance, after numerical simulation it is observed that the switching threshold can be controlled.

As another example, we consider shifted exponential chirp function and investigate effect of chirping on switching performance. It is shown that in the case of linear power of exponential function small switching threshold is needed.

In the case of nonlinear power of the exponential chirp function small switching threshold is obtained.

Finally in the case of sinc chirp function, it is observed that with increasing of the argument of the function the switching threshold is decreased considerably.

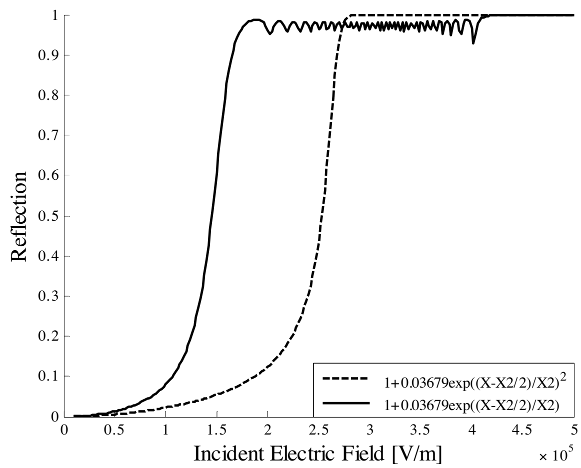

Figure 8. The reflection coefficient vs. incident electric field.

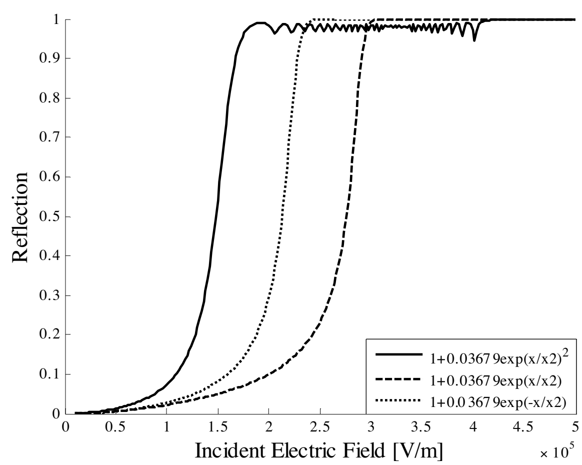

Figure 9. The reflection coefficient vs. incident electric field.

4. CONCLUSION

In this paper optical switching using Bragg grating has been considered. It was shown that the apodization and chirp function are key parameters for control of the switching performance. It was shown that using apodization function the slope of the transfer function can be increased and using the suitable chirp function the switching threshold is decreased.

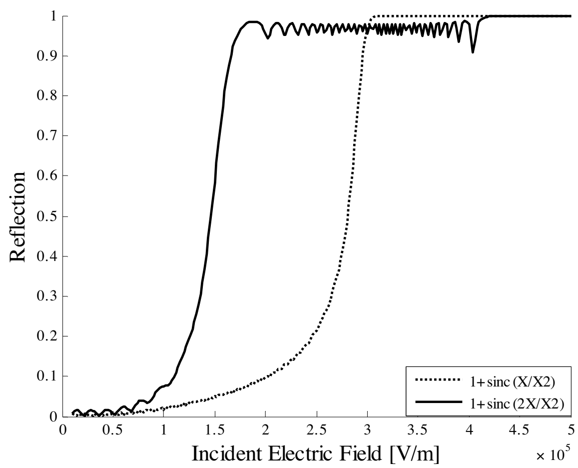

Figure 10. The reflection coefficient vs. incident electric field.

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