All optical spectral switches

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It is shown theoretically that the nonlinear optical Kerr effect can be used to build an all optical configuration controlling spectral switches. The main advantage in it is that it can greatly simplify the control method compared to previous schemes using the aperture mechanism or electro-optical one.

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Spectral switches have been extensively studied since it was first suggested in 2002 [1,2] and subsequently verified experimentally [3,4]. They are closely related to the singular optics [5] and spectral anomalies [6] that have contributed some important applications such as lattice spectroscopy [7,8] or spatial-coherence spectroscopy [9]. Afterwards they are applied to the digital data transmission work [10] and other fields [11,12]. At first, the more difficult methods [10] (varying the spectral bandwidth or the spatial coherence of the light source) are used to control the spectral switch; later the easier mechanical schemes that change the geometry of the aperture are suggested [11,12]. After that, the electro-optic modulation scheme [13] with Pockels effect is proposed to increase the transmitting speed from MHz (mechanical one) to GHz (electrical-optic one). In this paper we want to go one step further; the optical Kerr effect is used to build a simpler and whole optical configuration controlling the spectral switch without the external mechanical or electrical mechanism; while the high transmission rate can be maintained or even improved. The idea is presented in the following.

Consider a spatially, completely coherent light with Gaussian spectrum intensity as

$$I^{(i)}(\lambda) = I_0 \exp\left[-\frac{(\lambda-\lambda_0)^2}{\Gamma^2}\right], \tag{1}$$

where the superscript (i) in I denotes the incident light wave, I_0 the maximum intensity, λ_0 the center wavelength, and Γ the bandwidth. It is normally-incident on a double slit as in Fig. 1(a), and the detailed construction is shown in Fig. 1(b), where a nonlinear optical material is placed in front of the left slit. The aperture function of this geometry can be written as

$$g(x') = \left\{\exp(j\Delta\phi)\cdot\Pi\left(\frac{x'+\frac{a}{2}}{b}\right) + \Pi\left(\frac{x'-\frac{a}{2}}{b}\right)\right\}, \tag{2}$$

where $\Pi(x')$ is the rectangular function defined as $\Pi(x'/b) = 1$ for $|x'| \le b/2$ and $\Pi(x'/b) = 0$ for $|x'| > b/2$. The first and second rectangular functions in Eq. (2) represent the left and the right slit of the double slit respectively, which can be obtained from Fig. 1(b). The presence of the material with refraction index n causes a phase difference between the two slits by

$$\Delta\phi = k(n-1)d = \frac{2\pi(n-1)d}{\lambda}, \tag{3}$$

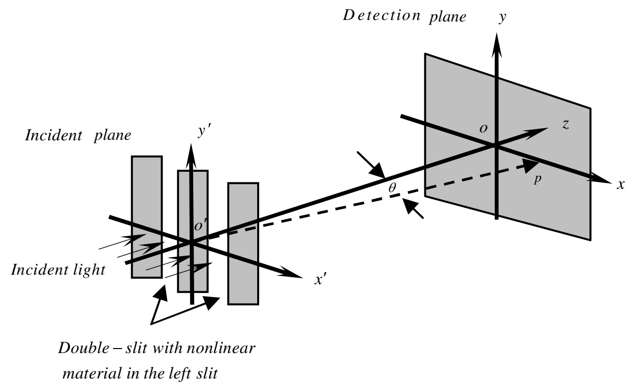
where d is the thickness of the material and k the wave number.

Since this nonlinear material can exhibit optical Kerr effect, its refraction index depends on the incident intensity $I^{(i)}$ as

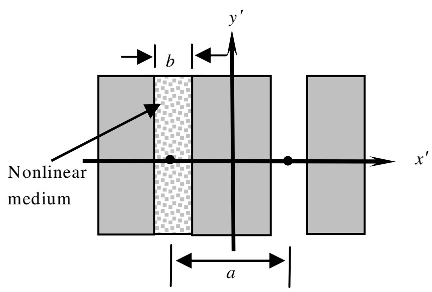
$$n = n_0 + n_2 I^{(i)}, \tag{4}$$

where n_0 is the ordinary refraction index and n_2 the second order coefficient [14]. The diffracted spectrum detected at position p in the far-field detection plane is

$$I(p,\lambda) \propto \frac{I^{(i)}}{\lambda^2}\cdot\cos^2\left(\frac{\Delta\phi}{2}+\pi f a\right)\cdot[b\,\mathrm{sinc}(\pi f b)]^2, \tag{5}$$



(a)



(b)

Fig. 1. (a) Basic configuration. An incoming light from the left is normally incident on a double slit. (b) Dimensions and structures of the double slit with a nonlinear material placed in the left slit.

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which can be derived using Fresnel–Kirchhoff diffraction and Fraunhofer approximation [2]. The sinc function above is defined as $\mathrm{sinc}(x) = \sin(x)/x$; the last two sinusoidal terms in Eq. (5) come from the Fourier transform of the aperture function [2,7] in Eq. (2). Also the spatial frequency f in Eq. (5) is $f = x/\lambda z = \tan(\theta)/\lambda$, where θ is the angle between $\overline{o'p}$ and optical axis $\overline{o'o}$ as in Fig. 1(a) for a p located on the x axis. With Eqs. (1), (3), and (4), the detected spectral intensity at θ can be represented as

$$I(\theta,\lambda) \propto I^{(i)} \times \left\{ \begin{array}{l} \frac{1}{\lambda^2}\cos^2\left(\frac{\pi d(n_0+n_2 I^{(i)}-1)}{\lambda} + \frac{\pi a \tan(\theta)}{\lambda}\right) \\ \times\left[b\,\mathrm{sinc}\left(\frac{\pi b \tan(\theta)}{\lambda}\right)\right]^2 \end{array} \right\}, \quad (6)$$

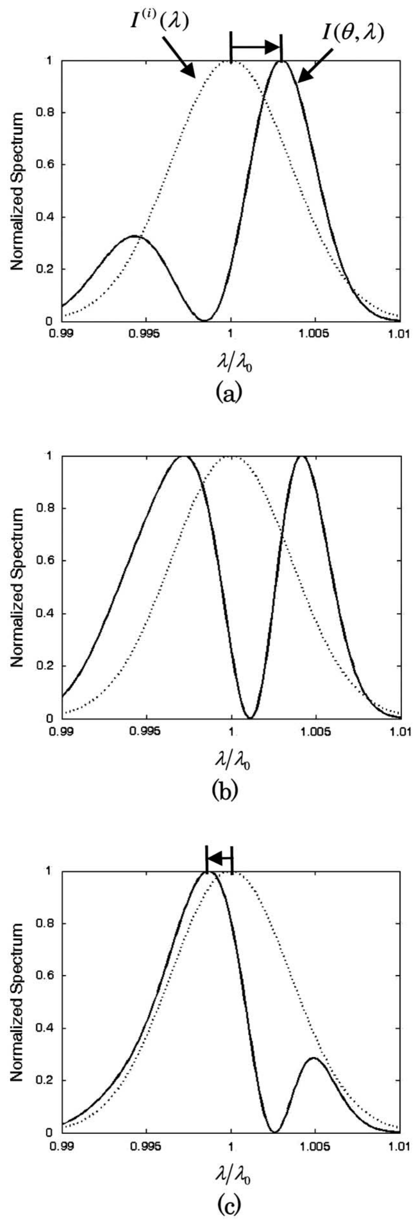

Fig. 2. Normalized spectral intensities for the incident light $I^{(i)}(\lambda)$ (dotted curve) and the diffracted light $I(\theta,\lambda)$ (solid curve): (a) I_0, (b) $3I_0$, (c) $5I_0$. (Each curve is normalized to its maximum value.)

where the term following $I^{(i)}$ is usually called the modifier because the incident spectrum is modulated (or modified) by it [2,7,11]. Apparently the modifier depends on the incident intensity $I^{(i)}$, which implies that the diffracted spectrum can be affected by varying $I^{(i)}$. To illustrate this point further with some numerical examples, the following practical parameters are used in calculations: $\lambda_0 = 0.5\ \mu$m, $2\Gamma = 0.01\lambda_0 = 5$ nm, $\tan(\theta) = 0.1$, $a = 100\ \mu$m, $b = 51.5\ \mu$m. For the nonlinear medium, BK-7 glass is used with $n_0 = 1.5$ and $n_2 = 4\times10^{-16}\ \mathrm{cm^2/W}$ [15]. It is pointed out that the material dispersion of n_0 can be safely neglected due to the limited bandwidth being about 5 nm. Figure 2(a) shows the normalized spectrum distribution for $I_0 = 2.5\times10^{12}\ \mathrm{W/cm^2}$, which can be achieved using a focused high power Nd:glass laser [15]. It is found that the spectrum maximum is redshifted and the amount of the shift is 0.6Γ. When the intensity increases to $3I_0$, Fig. 2(b) shows the spectrum splitting as two equal high peaks. Figure 2(c) is for $5I_0$, where the dominating peak is now blueshifted and the amount of the shift is -0.25Γ. From the plots in Fig. (2), it is obvious that the spectral maximum with blueshifts or redshifts (so called the spectral switch) can be controlled by varying the incident intensity, validating our proposition. A simple way, utilizing this property, to data transmission is indicated in Fig. 3. Consider there is a set of data, as in the first row of Fig. 3, needed to be sent to a direction $\tan(\theta) = 0.1$. If we designate blueshift and redshift as a bit of "1" or "0" respectively (the notations B and R are used to indicate the blueshift and redshift in the third row of Fig. 3), then by properly adjusting incident intensity, the blueshift (with $5I_0$) or the redshift (with I_0) of the spectrum's peak can be selected accordingly, as shown in the bottom row of Fig. 3; thus the data can be transmitted and demodulated by a receiver at that direction.

In summary, this is the first time that optical Kerr effect is suggested to be employed to cause spectral changes and to control the spectral switch, which substantially improves previous more laborious and complicated means. The merits of this scheme are the following. First, there are no moving parts as needed in mechanical cases and no extra external circuits as used in electro-optic cases; thus the execution of this scheme is very easy and straightforward, just through varying the incident light intensity. Second, the transmission rate can be even raised accordingly with this new structure, which is only limited by the incident light intensity control schemes; for example, Tera Hz speed can be achieved using the mode-locking laser technique.

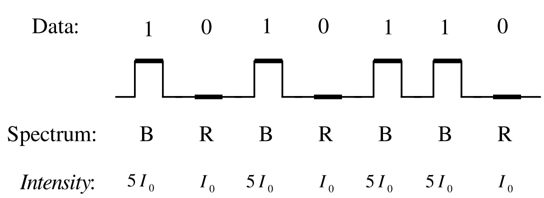

Fig. 3. Illustration for the data encoding and information transmission by controlling the light intensity I_0. The blueshift (B, in short) is associated with a bit of information such as "1," and the redshift (R, in short) is associated with a bit of "0."

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