Calculation and design for bistable optical devices of nonlinear interference filters

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Abstract. Three mathematical models for calculating and designing bistable optical devices (BODs) of nonlinear interference filters are compared and the necessity of using the accuracy matrix model based on the principle of thin-film optics to study optical bistabilities of nonlinear interference filters is confirmed. The relationships of important parameters, such as $\delta I_0'$, δI_t, and I_0, with the initial detuning δ, which are very helpful in designing the BODs, are calculated and plotted. The dispersive relations of ZnSe thin-film are introduced into the method to make the theoretical method self-consistent. Finally, experimental results of a BOD of nonlinear interference filter whose construction is calculated using this method are given.

Subject terms: optical bistability; initial detuning; coating wavelength; dispersive relation.

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1 Introduction

The optical bistabilities of ZnSe interference filters have been studied since 1977 when Karpushko and Sinitsyn first reported their experimental results.

Because the bistable optical device (BOD) of a nonlinear interference filter is similar to a Fabry-Pérot etalon, many characteristics of a BOD can, to some extent, be effectively discussed and studied using a Fabry-Pérot etalon.[1–7] In some papers, the energy absorbed by the spacers was considered as the thermal source inducing refractive index nonlinearity of thin films, whereas the energy absorbed by the stacks acting as high reflection mirrors around the spacers was ignored. This procedure, however, is not always reasonable in every case. Wherrett et al.,[8] for example, studied the roles of the spacers and the stacks in the nonlinear interference filters operating optical bistabilities, and emphasized that the stacks in filters not only provide high reflectivity for the Fabry-Pérot etalon but can also produce nonlinear refractive index change under strong laser irradiance, especially in active stacks; that is, the change of the nonlinear refractive index is induced by the total energy absorbed by the spacers and the stacks of the filters. Therefore, considering the actions of various high-low refractive index materials is very useful for studying the optical bistabilities of nonlinear interference filters.

In this paper, we briefly compare three mathematical models for calculating and studying nonlinear interference filter BODs and confirm the necessity of using the accurate matrix model, model 3 in Sec. 2. Then, we calculate some important parameters of interference filter BODs and plot their relation curves with initial detuning δ in Sec. 3. To make our method more self-consistent and to obtain more initial detuning δ accuracy, we provide an approach for determining the detuning δ in weak irradiance by introducing the dispersive relation of ZnSe thin film into our method and provide experimental results supporting our method in Sec. 4. Finally, in Sec. 5, we present our conclusions.

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2 Theoretical Background and Comparisons

The general construction of Fabry-Pérot type interference filters $(HL)^p(HH)^m(LH)^p$, where H indicates a quarter wavelength ($\lambda/4$) thickness of the high refractive-index material (ZnSe), and its refractive index is represented with n_H; L indicates a $\lambda/4$ thickness of low index material (cryolite Na_3AlF_6), and its refractive-index is represented with n_L; p and m are integers; and λ is wavelength. As is well known, an optical bistable transmission process is produced through a combination or an incorporation of transmittivity with a modulated relation that is determined by the construction of Fabry-Pérot etalon and a nonlinear relation that is determined by the nonlinearity of the materials. The simplified transmittivity of Fabry-Pérot-type interference filters can be described as in Eq. (1), where the absorption of the stacks has been left out.[1] Based on this, we can improve the accuracy of the relation as Eq. (2) by considering the absorption of the stacks as well as the spacer. We call Eqs. (1) and (2) models 1 and 2, respectively. Of course, both model 1 and model 2 are approximate because they are based on the theory of the Fabry-Pérot etalon; however, model 2 proves to be closer to the real case.

$$\tau = a(1-R)^2/[(1-Ra)^2(1+F\sin^2\Phi)] \ , \tag{1}$$

$$\tau = [a(1-R)]^2/\{[(1-Ra)^2+1](1+F\sin^2\Phi)\} \ , \tag{2}$$

where $a=\exp(-\alpha L)$; α and L are the absorptive coefficient and the physical thickness of spacer, respectively; $F=4Ra/(1-Ra)^2$; R is the effective reflectivity of the stacks around the spacer; Φ is the phase change in a single path; and τ is transmittivity. The third model can be obtained from the optics principle of thin film, i.e., matrix relations[3] as Eqs. (3) through (7):

$$\tau = \frac{4\eta_o \eta_s}{(B\eta_o + C)(B\eta_o + C)^*} , \quad (3)$$

where

$$\begin{pmatrix} B \\ C \end{pmatrix} = \prod_{j=1}^{4p+1} \begin{pmatrix} \cos\delta_j & (i/\eta_j)\sin\delta_j \\ i\eta_j \sin\delta_j & \cos\delta_j \end{pmatrix} \begin{pmatrix} 1 \\ \eta_s \end{pmatrix} , \quad (4)$$

$$\delta_j = (2\pi/\lambda) L_j N_j \cos\theta_j , \quad (5)$$

$$\eta_j = \begin{cases} N_j \cos\theta_j & \text{(for } S \text{ wave)} \\ N_j/\cos\theta_j & \text{(for } P \text{ wave)} \end{cases} , \quad (6)$$

$$N_j = n_j - k_j , \quad (7)$$

where η_j is the optical conductance of the j'th layer film and, in a similar manner, η_o and η_s are the optical conductances of the air and the substrate, respectively. Here N_j is the complex index of the j'th layer film, and n_j, k_j, and θ_j are the effective refractive index, the extinction coefficient, and the refractive angle of the j'th layer film, respectively.

We select an interference filter with the construction $p=3$ and $m=4$, let $\lambda=514$ nm and $\alpha=600\ \text{cm}^{-1}$, and then calculate its transmission spectra using models 1, 2, and 3 as lines 1, 2, and 3, respectively, as depicted in Fig. 1. These three spectrum lines are obviously different.

For the nonlinear relation of film materials, we consider just the refractive index change of a high-index material (ZnSe) with the change of light irradiance (that of low index can be ignored).[1,2,8,9] Thus, we select the simplest relation, Eq. (8), when processing the nonlinearities of high-index materials:

$$n(I_c) = n_o + n_2 I_c , \quad (8)$$

where n_2 is about $0.0014\ \text{cm}^2/\text{kW}$ according to our measured results and I_c is really the laser irradiance within the nonlinear material. Of course, $n(I_c)$ is not a linear relationship of irradiance I_c, but it is close to a linear relation, and it is reasonable to take the linear relation of Eq. (8) in our subject. For ZnSe film $n_o=2.7$, if $\Delta n = n(I_c) - n_o$, and the phase relation is represented as

$$\Phi(I_c) = m\pi + \Delta n \cdot 2\pi/\lambda - \delta . \quad (9)$$

Substituting Eqs. (8) and (9) into models 1, 2, and 3, respectively, we obtain the input/output relation curves as lines 1, 2, and 3, shown in Fig. 2 with respect to models 1, 2, and 3, where we take the initial detuning as $\delta = 4.4$ nm. It is obvious that curve 3 is the most accurate. Therefore, it is necessary to use the matrix relations of model 3 in studying and designing nonlinear interference filter BODs.

3 Construction Design

As is well known, the performance evaluation of BODs depends on several major parameters.[10] Where $I_o\uparrow$ is the switching-on intensity of a BOD and $I_o\downarrow$ is the switching-off intensity, $\delta I_o = I_o\uparrow - I_o\downarrow$ indicates the width of the optical bistability, and is a significant parameter. In addition, $I_t\uparrow$, $I_t\downarrow$, and δI_t ($=I_t\downarrow - I_t\uparrow$), which correspond

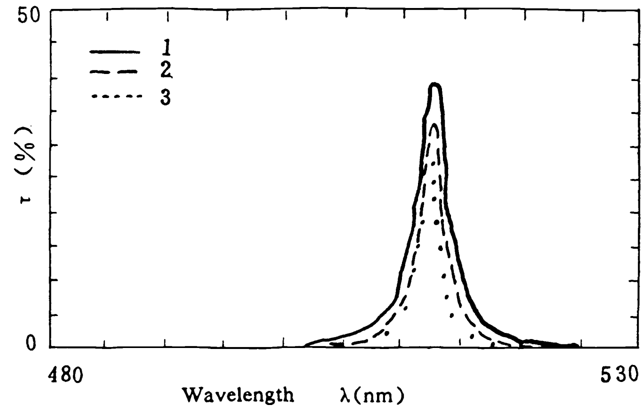

Fig. 1 Spectra calculated by three calculating formulas. Line 1 is from model 1, line 2 from model 2, and line 3 from model 3; $p=3$ and $m=4$.

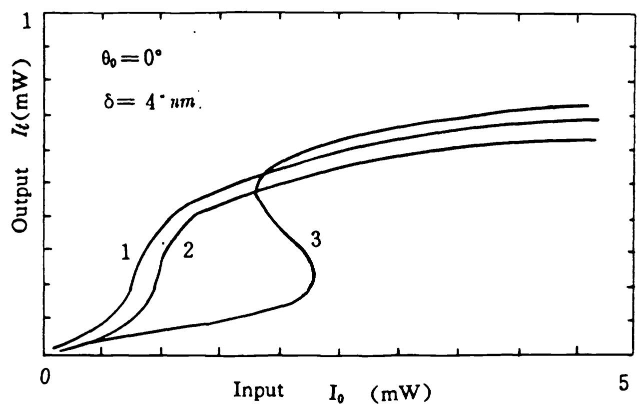

Fig. 2 Optical bistable characteristic lines simulated by the three models. Line 1 is from model 1, line 2 from model 2, and line 3 from model 3; $\delta=4.4$ nm, $p=3$, and $m=4$.

to the switching intensities and optical bistability width respectively, are worth considering in designing BODs.

First, let us study in detail and calculate the relations of δI_o, δI_t, and $I_o\uparrow$ with the initial detuning δ for a variety of constructions with different spacer thicknesses and stack numbers using the matrix formulas of model 3. The calculated results are shown in Fig. 3. We can easily see from Fig. 3 that many different effects on optical bistabilities are produced by the different spacer thicknesses, as are produced by the different stack numbers. Hence, in terms of our practical requirements for δI_o, δI_t, and $I_o\uparrow$, we can select the construction with the relation curves in Fig. 3.

One interesting finding from the curves in Fig. 3 is that the stack number directly affects critical detuning values δ_c for optical bistabilities. In addition, Fig. 3 may provide other important references helpful for studying nonlinear interference filter BODs. In fact, the evaluation of a BOD rests on the practical requirements and conditions of the experiments and applications. When the incident angle increases, these relationships change. As a result, the critical detuning value δ_c for producing optical bistabilities decreases with the increase of the incident angle, and even when the incident angle reaches some value, the critical detuning value δ_c for optical bistabilities will reach zero

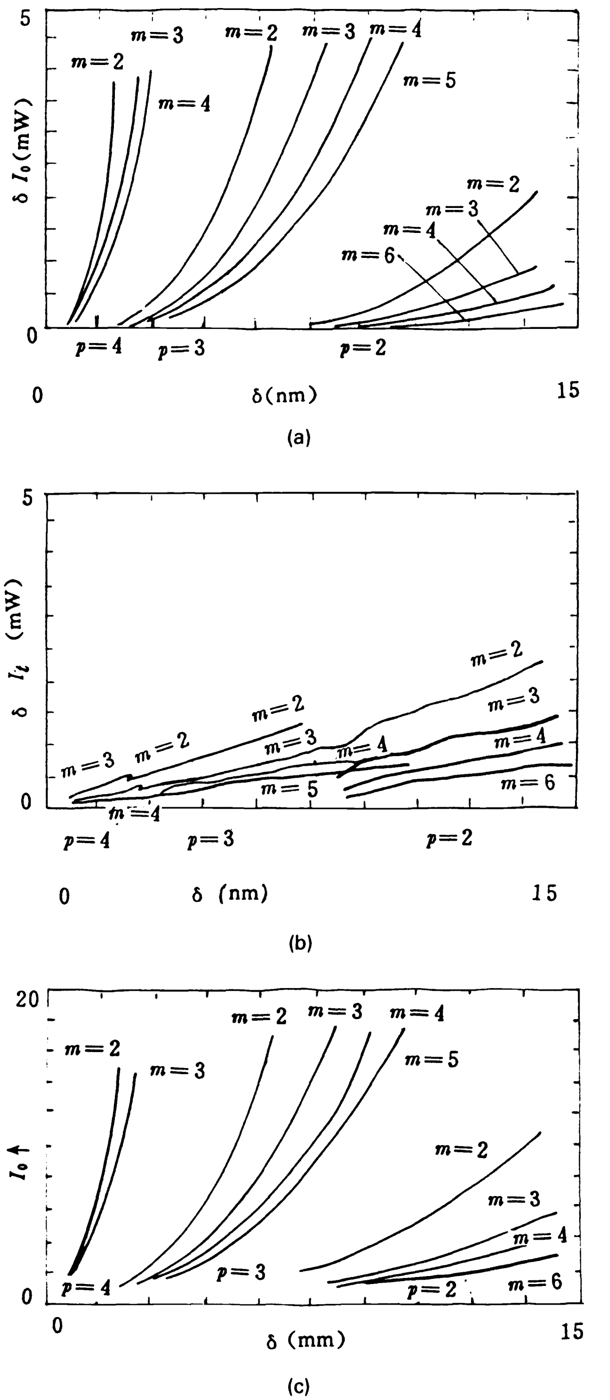

Fig. 3 Relation curves of δI_o, δI_t, and $I_o \uparrow$, with the initial detuning δ (a) for δI_o, (b) for δI_t, and (c) for $I_o \uparrow$.

and continue to decrease to negative values as the incident angle continues to increase. This is why the author of Ref. 1 depended on increasing incident angles to observe bistable optical phenomena when δ_c was negative.

4 Determination for Coating Wavelength

As discussed, a BOD must have a sufficient detuning value when it is coated under weak irradiance to make its optical bistabilities occur when irradiance increases to the situation that meets the conditions for optical bistabilities to occur. For a nonlinear interference filter BOD, the peak wavelength λ' (i.e., the coating wavelength) under weak irradiance must be smaller than the laser wavelength λ_o that induces the index nonlinearity of the high-index materials ($\lambda' < \lambda_o$) so that the thermal index nonlinearity will cause the peak wavelength (λ') to approach the laser wavelength (λ_o), inducing index nonlinearity. Finally, optical bistability occurs when resonance conditions are met ($\lambda' \approx \lambda_o$). Therefore, coating wavelength λ' must be calculated in detail to ensure that the nonlinear interference filter BODs have the required initial detuning δ under weak irradiance. An interference filter, however, is coated by a quarter wavelength coating λ', which meets the peak transmission of weak irradiance, and both high- and low-index materials are dispersive.[11] Hence, we introduce the dispersive relation of ZnSe thin film[12] to resolve the problem:

$$n'^2 = 3.71 + \frac{2.19\lambda'^2}{\lambda'^2 - 0.105} \ , \ (\lambda' \text{ in micrometers}) \qquad (10)$$

where

$$\lambda' = 4n'L \ , \qquad (11)$$

and L is the physical thickness meeting the detuning δ of each coating layer of ZnSe. If the spacer is composed of 2-m coating layers of quarter wavelength, then

$$L = \frac{1}{n_{Ho}} \left(\frac{\lambda_o}{4} - \frac{\delta}{2m} \right) \ , \qquad (12)$$

where n_{Ho} is the linear refractive index of the high-index material of the 514-nm line. Substituting Eqs. (11) and (12) into Eq. (10), we can determine the refractive index n' in terms of the coating wavelength λ'. Furthermore, we can determine the coating wavelength λ' with Eq. (12). For example, if spacer thickness m is 4, $\delta = 4.4$ nm, $\lambda_o = 514$ nm, and $n_{Ho} = 2.7$, we obtain $L = 47.39$ nm, $n' = 2.711$, and $\lambda' = 513$ nm. When δ is larger, it is necessary to introduce the dispersive relation, Eq. (10). Thus, our design method for calculating and designing nonlinear interference filter BODs is more self-consistent and is made more effective by introducing the dispersive relation for a nonlinear material. Figure 4 shows the experimental results for a BOD whose construction is selected according to Fig. 3, namely, $p = 3$, $m = 2$, and $\delta = 6$. We then obtain $L = 47.04$ nm with Eq. (12). Furthermore, $n' = 2.713$ and $\lambda' = 511$ nm are obtained using Eqs. (10) and (11). For the experimental results shown in Fig. 4, switching-on time is around 50 μs and switching-off time is around 80 μs.

5 Conclusions

We briefly compare and discuss three theoretical models for calculating and studying optical bistabilities through calculating their transmission spectra and interference filter BODs. In the paper, we calculate the relations of the parameters δI_o, δI_t, and $I_o \uparrow$ with the initial detuning δ, which are useful parameters and build the foundation for designing and evaluating nonlinear interference filter BODs. In fact, this paper provides an effective and convenient method for designing and studying nonlinear interference filter BODs.

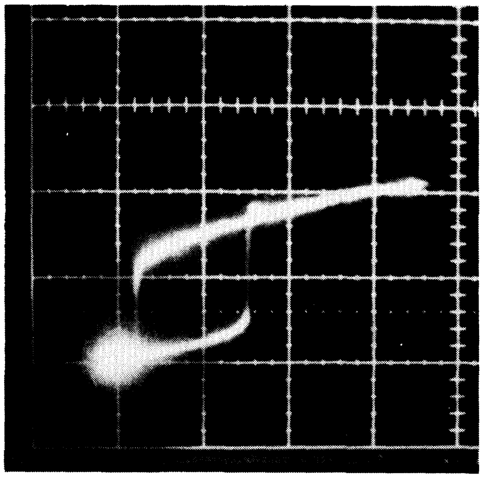

Fig. 4 Experimental results for a nonlinear interference filter BOD designed with our method: $p=3$, $m=2$, $\delta=6$, $\lambda'=511$ nm, switching-on time is around 50 μs, and switching-off time is around 80 μs.

In addition, to determine the coating wavelength and make our method more self-consistent, we introduce the dispersive relations of the nonlinear material ZnSe. Our design and calculation results are very accurate and are experimentally supported.

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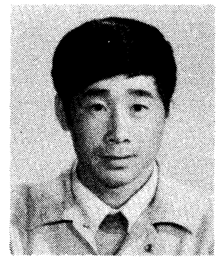

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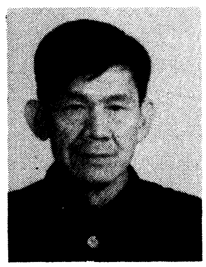

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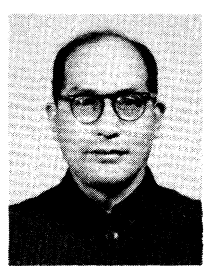

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