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Switching mirror in the CdTe-based photonic crystal

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Theoretical investigations, modeling and design of a Bragg mirror (photonic crystal structure) in the CdTe-based material system are presented. It is shown that, in addition to the third-order nonlinearity (Kerr-like effect), the two-photon absorption and the resulting free-carrier refraction have to be included in the analysis and design. Inclusion of changes in the refractive index with the square of the light intensity (fifth-order nonlinearity) leads to desirable functional features of the switching mirror. The analysis provides insight into the complex nonlinear effects and serves as a tool for designing a nonlinear intra-cavity mirror for a novel pulsed laser. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1954876]

Optical nonlinear properties of semiconductor materials have been used in important applications such as optical limiting or bistable switching.[1,2] Materials GaAs and InP have been investigated extensively theoretically as well as experimentally whereby the third-order nonlinearity effects (Kerr-like phenomenon—the refractive index is a function of the intensity) near the band edge were exploited.[3,4] Studies of CdTe crystals at room temperature revealed that optical nonlinear effects due to the photoexcited free carriers generated via two-photon absorption (fifth-order nonlinearity—the refractive index is a function of the square of the intensity) need to be included if applications are to be considered.[5]

In this letter, a nonlinear Bragg mirror in the $CdTe/SiO_2/TiO_2$ material system is designed as a potential intra-cavity all-optical switching element for a 1079.5 nm pulsed laser. The requirements for the reflectivities in the off and on states were 99% and 10%, respectively. The expected switching intensity was in the range between 50 and 300 MW/cm^2.

For the nonlinear material to be used, CdTe, and the given operating wavelength of the laser, $\lambda = 1079.5$ nm, two effects determine the nonlinear refractive index change necessary for switching. One is the third-order nonlinearity where the index change is dependent on the intensity of light (single-photon absorption resulting in bound-electronic refraction). The other one is the fifth-order nonlinearity where the index change is dependent on the square of the intensity (two-photon absorption resulting in free-carrier refraction). Both these effects have the same sign (negative) and, depending on the actual intensity inside the material, one or the other or both contribute to the nonlinear change in the refractive index. Generally, the single-photon effect dominates at lower intensities while the two-photon-initiated refraction effect dominates at high intensities. Both effects compete with the thermal refractive index changes, which are positive and are caused by the linear and nonlinear absorption in the material.

The residual linear absorption of CdTe at $\lambda = 1.064$ μm is $\alpha = 0.3$ cm^{-1}. For thicknesses of up to $d = 1$ μm, which is required, the loss of intensity $I = I_0 \cdot e^{-\alpha.d}$ is negligible (0.003%). The nonlinear absorption of CdTe at $\lambda = 1.064$ μm is $\beta = 22$ cm/GW. The loss in this case depends on the actual intensity. For the same thickness $d = 1$ μm, and assuming a large intensity $I_0 = 1$ GW/cm^2, the loss of intensity $I = I_0/(1 + \beta \cdot I_0 \cdot d)$ is only 0.2%, which is also negligible.

The bound-electronic refraction is linear with intensity, $\Delta n_L = \gamma \cdot I$, and the free-carrier refraction is quadratic, $\Delta n_{NL} = c \cdot \sigma \cdot I^2$. The values of material constants γ, c, σ were taken from Ref. 5 (see below). Considering an intensity $I_0 = 1$ GW/cm^2 and a pulse width $t_0 = 0.5$ ns, the total refractive index change $\Delta n_T = \Delta n_L + \Delta n_{NL} = -3 \cdot 10^{-4} - 8 \cdot 10^{-2}$. One can see that the free-carrier refraction dominates. The break-even intensity is about 3.5 MW/cm^2.

The thermal refractive index change is caused only by the nonlinear absorption. For the same parameters, one obtains $\Delta n_{th} = +5 \cdot 10^{-4}$. This is comparable with the bound-electronic refraction and may very well eliminate its effect. However, it is two orders of magnitude smaller than the free-carrier refraction, which will thus dominate the overall refractive index change.

The nonlinear Fabry-Pérot resonator uses a nonlinear material in between the two high-reflecting mirrors. Bistable switching is possible in such a structure depending on its thickness and the refractive index of the material inside. Graphical solutions, found in basic textbooks,[1] for a nonlinear resonator filled with a material having the bound-electronic refraction illustrate that high contrast is virtually impossible to achieve, no matter where one places the initial detuning. In fact, only when the resonator is being switched back to the high-reflectivity state, is a high extinction ratio obtained. Experiments confirmed this feature in numerous instances.

For the purpose of this work and based on the material considerations above, a nonlinear Fabry-Pérot performance was evaluated considering the free-carrier refraction effect instead of the bound-electronic effect. A graphical solution is shown in Fig. 1. Because of the quadratic dependence of the refractive index change on the intensity, the parametric set used for finding the common solution is not a set of straight lines anymore but rather that of parabolas. It is, however, seen again that achieving high contrast for the switching state going from a high reflectivity to a low one is not possible; in fact, the situation is even worse because of the parabolic behavior. It is interesting to note that the nonlinear shapes of both curves suggest that some chaotic behavior of

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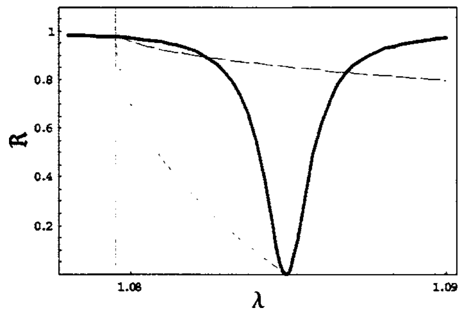

FIG. 1. Diagram of bistable switching in a nonlinear Fabry-Pérot cavity with the free-carrier nonlinearity. The vertical line corresponds to the linear nondetuned case. The short-dashed curve corresponds to the low incident intensity, while the long-dashed curve represents the high intensity case. Cross sections between the resonator's characteristic (thick line) and the intensity curves yields the corresponding graphical solution for a given operating point.

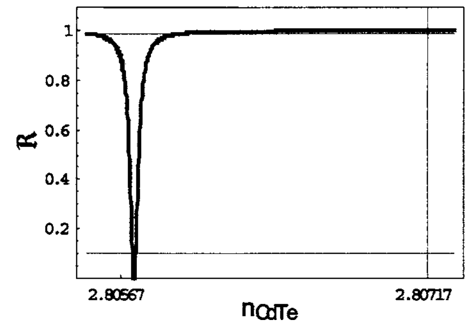

FIG. 2. Reflectivity vs refractive index change in the CdTe layers with at 1.0795 μm. Horizontal lines correspond to the required reflectivities of 10% and 99%, respectively. The vertical line denotes a low incident intensity, while the minimum reflectivity is at a high incident intensity. High-extinction-ratio switching is achieved.

nonlinear optical systems observed in experiments, and in most cases attributed to thermal effects and noise, may, in fact, be a result of inherent indeterminacy of an operating point (curves intersection) at a given time. More studies of this idea are under way.

Experiments with a CdTe nonlinear Fabry-Pérot etalon exhibited some switching and other nonlinear functions, such as optical limiting and pulse compression. The switching extinction ratios were quite poor.[5] Changes of the output intensity between only 20% and 65% were obtained, which is not acceptable for the purposes of this design. As a conclusion, there does not seem to be a way to employ a single-layer CdTe nonlinear Fabry-Pérot resonator for achieving the required switching contrast between 10% and 99%.

The periodic multilayered structure has better properties than the Fabry-Pérot resonator in terms of achievable contrast and a much broader low-reflectivity region with possible sharper stop-band edges. Optical bistable switching in nonlinear semiconductor distributed-feedback (DFB) showed good properties including better contrast.[4] A simple distributed-feedback structure with a small number of layers, using $CdTe/SiO_2$ material parameters, was studied. It was found that already for only four double layers, over 85% reflectivity in the stop band and less than 10% reflectivity outside it could be achieved.

Periodic multilayers offer much better performance in terms of contrast ratio, switching threshold and the overall required thickness of the structure. They also have more design freedom when fine tuning of the performance is necessary with respect to the operating wavelength and the achievable refractive index change. In addition, with proper phase matching, one can design a periodic structure to accommodate internal field distribution optimally, which is impossible with simple Fabry-Pérot resonators.

However, this does require very extensive multiparameter design procedure which is time consuming because it represents basically finding an optimum of a functional. A general algorithm does not exist for such problems, and an approach based on experienced intelligent trial and error process needs to be employed. The numerical approach used is based on a classical transfer-matrix method modified and extended to include nonlinear effects. An iteration is necessary for every input intensity in order to determine the output. The program is written in Mathematica. Given refractive indices and their chnages, various thicknesses of layers and the number of layers were tested while targeting the optimization of the mirror performance.

For the nonlinear material, CdTe, and the given operating wavelength of the laser, $\lambda = 1079.5$ nm, the fifth-order nonlinearity, where the index change is dependent on the square of the intensity, is employed in the switching mechanism. For the required intensity of about 140 MW/cm^2, one can estimate the achievable refractive index change from an expression: $\Delta n_{NL} = c \cdot \sigma \cdot I^2$, where $\sigma = -5.2 \cdot 10^{-21}$ cm^3 and $c = 0.23\beta \cdot t_0/(h \cdot \nu)$. With t_0 being the pulse width of about 500 ps and $\beta = 25$ cm/GW, $c \cong 15$ cm/W^2. This yields $\Delta n_{NL} \cong -1.5.10^{-3}$. This is then the approximate value of the refractive index change of the nonlinear material (CdTe), which should bring the high-reflectivity state to the low-reflectivity state.

The best performance obtained is with the so-called *combined distributed-feedback/Fabry-Pérot* structure.[6] In this periodic multilayer (today called a one-dimensional photonic crystal with a defect), two resonances are combined constructively to yield a very sharp and narrow reflectivity or transmissivity peak. The design takes advantage of these features by tuning the parameters that are variable, i.e., basically thicknesses of all layers, to satisfy all requirements with achievable refractive index changes in the nonlinear distributed feedback structure.

First, linear top and bottom mirrors were designed with high reflectivities (99%) at the operating wavelength of 1.0795 μm using double layers of SiO_2/TiO_2. A minimum of six periods was needed. The top mirror starts with TiO_2, while the bottom mirror is reversed, to accommodate the fabrication process.

Second, the DFB multilayer stack was designed to obtain a high reflectivity ($>99\%$) in the stop band and a low reflectivity outside it. A minimum of ten periods was required. The operating wavelength was placed quite close to the minimum rather than the maximum for the reasons of obtaining the high reflectivity of the whole combined structure.

Third, the DFB stack was placed between the mirrors to form a Fabry-Pérot cavity. Both the cavity and the DFB have their own resonances which now have to be matched constructively with the help of the phase matching layer today it is called (a defect) in this one-dimensional photonic crystal. TiO_2 was chosen for this layer, again to accommodate the fabrication process as simply as possible. The combined structure exhibits, at $\lambda = 1.0795$ μm, the reflectivity of

Superstrate	Air
Top Mirror	6 x TiO_2/SiO_2 0.12/0.185 μm
Matching Layer	1 x TiO_2 0.147 μm
Distributed Feedback	10 x SiO_2/CdTe 0.0725/.12 μm
Bottom Mirror	6 x SiO_2/TiO_2 0.185/0.12 μm
Substrate	SiO_2

Refractive indices:

$n_{SiO2} = 1.461$
$n_{TiO2} = 2.24$
$n_{CdTe} = 2.80717$

FIG. 3. Nonlinear CdTe-based Bragg mirror (one-dimensional photonic crystal with a defect).

0.9922. Half a nanometer away, the reflectivity drops to its minimum of 0.0115. The requirement is thus satisfied.

The calculations were also performed for a fixed wavelength (1.0795 μm) while the refractive index of the CdTe layers in the DFB stack was varied in dependence on intensity. Figure 2 shows the result. The minimum reflectivity peak is now correctly on the left from the operating point, because a negative nonlinear refractive index change takes place as a result of increasing the incident intensity. As can be seen from the figure, the operating point is at $n_{\mathrm{CdTe}} = 2.80717$ for low intensity (linear case) while the required refractive index change to reach the minimum (nonlinear case) is about $1.5 \cdot 10^{-3}$. The requirement is thus also satisfied. The total structure including all its parameters is shown in Fig. 3.

The fifth-order nonlinearity in CdTe was exploited to design an all-optical switching mirror for a pulsed laser. Stringent requirements have been met. Fabrication feasibility was considered and a realistic design was achieved.

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