Combined distributed feedback and Fabry–Perot structures with a phase-matching layer for optical bistable devices

J. He and M. Cada
Technical University of Nova Scotia, Department of Electrical Engineering, P. O. Box 1000, Halifax, B3J 2X4 Canada

(Received 26 February 1992; accepted for publication 25 August 1992)

A combined distributed feedback and Fabry–Perot (DFB/FP) structure with a phase-matching layer is proposed for optical bistable devices. Using a simple and versatile nonlinear transfer-matrix method, we demonstrate that the DFB/FP structure can have a much lower bistability threshold than a single DFB structure with a comparable total thickness. The combined structure can also have lower threshold and less sensitivity to absorption than a traditional nonlinear Fabry–Perot etalon.

A dispersive optical bistable device usually consists of a nonlinear material with an intensity-dependent refractive index and an optical resonant structure. In the past decade, semiconductor nonlinear material such as GaAs or GaAs/GaAlAs multiple quantum wells have received considerable attention because of their large nonlinearity in the vicinity of electronic band edge.[1–3] However, the optical loss in these materials is also high at such wavelengths. This reduces significantly the optical resonance usually obtained through a Fabry–Perot cavity. Therefore, the seeking of a better structure which could utilize the large nonlinearity while minimizing the effect of high absorption would be of great interest.

Recently, nonlinear periodic layered structures have been proposed for optical bistable operation, particularly GaAs/AlAs systems,[4] and optical logic functions have been demonstrated experimentally.[5] The optical resonance is obtained through the distributed feedback (DFB) mechanism. This structure is advantageous for lossy nonlinear material because it incorporates another constituent (e.g. AlAs) which is nonabsorptive. While the overall absorption is reduced, the nonlinearity remains high because, by appropriate design, the optical field can be mainly confined in the nonlinear layers.

Several theoretical works related to the topic should be mentioned. Winful *et al.*[6] first predicted optical bistability in nonlinear DFB waveguides. Chen and Mills[7] calculated the nonlinear optical responses of superlattices and related them to "gap solutions." Similar calculations using different approaches and considering different conditions have been done by several other authors.[8–10] The effect of end reflections has also been analyzed for the DFB structures.[11–13]

Although the periodic DFB structure has a better match between the nonlinearity and the optical field, it usually needs a large number of periods to obtain a sharp and strong resonance, especially when the refractive indices of the two constituents are not very different. This increases the difficulty for the growth of samples with techniques such as molecular beam epitaxy. A thick sample will need excessive growth time and make it difficult to keep a uniform periodicity along the growth axis. Usually the total thickness of the structure should be limited to around 5 μm. Consequently, the linewidth of the resonance peak of interest is usually larger than 2 nm in a GaAs/AlAs system.[5]

To solve this problem, we propose to place the DFB structure into a Fabry–Perot (FP) etalon. The mirrors of the Fabry–Perot cavity can be Bragg reflectors fabricated in the same growth process using the same materials. Though the Bragg reflectors are also periodic multilayers, their periods are slightly different from that of the DFB structure. The operating laser wavelength lies within the stop band of the mirror structure, while it is at the resonant transmission peak (with a slight detuning) of the DFB structure. In such a combined DFB/FP structure, the field intensity in the DFB region will be further increased by the resonance of the Fabry–Perot cavity. Since the resonance is now produced by two different mechanisms, a phase-matching layer between the DFB structure and one of the mirrors is necessary to obtain a sharp resonance peak and a high reflectivity contrast. This letter is to report our theoretical demonstration of the superiority of this combined structure over a single periodic structure with natural front-facet reflection or a Fabry–Perot etalon.

For the combined DFB/FP structure, the analytical methods used for nonlinear Fabry–Perot etalons[14] are no longer applicable. The coupled mode method for periodic structures[4,6] cannot be used either because the mirrors and the DFB region in the structure have different periodicities. We develop therefore a numerical approach based on the transfer-matrix method which can be used for arbitrary multilayer structures.

We consider plane waves propagating in an arbitrarily layered structure in the direction perpendicular to the interfaces (z axis). The electric field E in each layer, can be described by

$$E = Ae^{-\alpha z}e^{ikz} + Be^{\alpha z}e^{-ikz} \tag{1}$$

where k is the propagation wavenumber in the layer and α is the amplitude absorption coefficient. In the linear case, when the transmitted amplitude is given, one can use the transfer-matrix method[15] to calculate the electric field layer by layer from the transmission medium to the incident medium. However, in the nonlinear case, A and B are not constant in each layer because of the intensity-dependent refractive index. To overcome this difficulty, we divide each layer into a large number of sublayers whose thicknesses are very small compared to the wavelength so that the intensity in each sublayer can be considered constant. If the intensity-dependent refractive index of each sublayer is determined, the transfer-matrix method can be employed in the same way as the case of linear media. Usually, dividing each layer into 20 sublayers is enough to give an accurate result. In the following formalism, we consider each sublayer as a distinct layer.

The wave amplitudes in two adjacent layers can be related by boundary continuity conditions which can be written in the matrix form:

$$\begin{pmatrix} A_{m+1} \\ B_{m+1} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1+Z & 1-Z \\ 1-Z & 1+Z \end{pmatrix}\begin{pmatrix} e^{-\alpha_m d_m} e^{ik_m d_m} & 0 \\ 0 & e^{\alpha_m d_m} e^{-ik_m d_m} \end{pmatrix} \times \begin{pmatrix} A_m \\ B_m \end{pmatrix} \quad (2)$$

where $Z = n_m / n_{m+1}$, m is an integer indicating the layer number and d_m is the thickness of the mth layer.

For simplicity, we neglect the saturation of absorption as well as the nonlinear saturation in this letter. The nonlinear refractive index can then be written in the form of $n = n^{(0)} + \eta |E|^2$, where $n^{(0)}$ is the linear refractive index and η is a constant describing nonlinear refraction. The refractive index in the mth layer can then be written as

$$n_m = n_m^{(0)} + \eta_m |A_m + B_m|^2. \quad (3)$$

From the boundary conditions (2), we can also derive

$$n_{m+1} = n_{m+1}^{(0)} + \eta_{m+1} |A_m e^{-\alpha_m d_m} e^{ik_m d_m} + B_m e^{\alpha_m d_m} e^{-ik_m d_m}|^2. \quad (4)$$

Therefore, from the wave amplitudes A_m and B_m in one layer, we can calculate the intensity-dependent refractive index in this layer as well as the one in the next layer by using Eqs. (3) and (4). The amplitudes in the next layer A_{m+1} and B_{m+1} can then be obtained with the transfer-matrix Eq. (2).

Though the above method is relatively simple compared to other models, no slowly-varying-envelope approximation is made. Theoretically, it can give exact solution if the thicknesses of sublayers are infinitely small. In the linear case, the solution is always exact, regardless of how many subdivisions are made in each physical layer.

The linear and nonlinear reflectivity spectra calculated with the above method for a DFB/FP structure are shown in Fig. 1. The structure consists of 7 periods of GaAs/AlAs quarter-wave-thick layers as the back mirror, 20 periods of the DFB structure, a 36.5 nm thick AlAs phase matching layer, and finally 7.5 periods of the same quarter-wave-thick layers for the front mirror. The thicknesses of the GaAs and AlAs layers, are, respectively, 62.3 and 75.5 nm in the mirrors, and 49.7 and 80.0 nm in the DFB region. The total thickness of the structure is about 4.6 μm, with a GaAs substrate. The property parameters of GaAs and AlAs are the same as those used in Ref. 4. The linear reflectivity spectrum[16] of the structure exhibits a very sharp negative peak at 889.6 nm, with a linewidth (full width at half maximum) of about 1.2 nm.

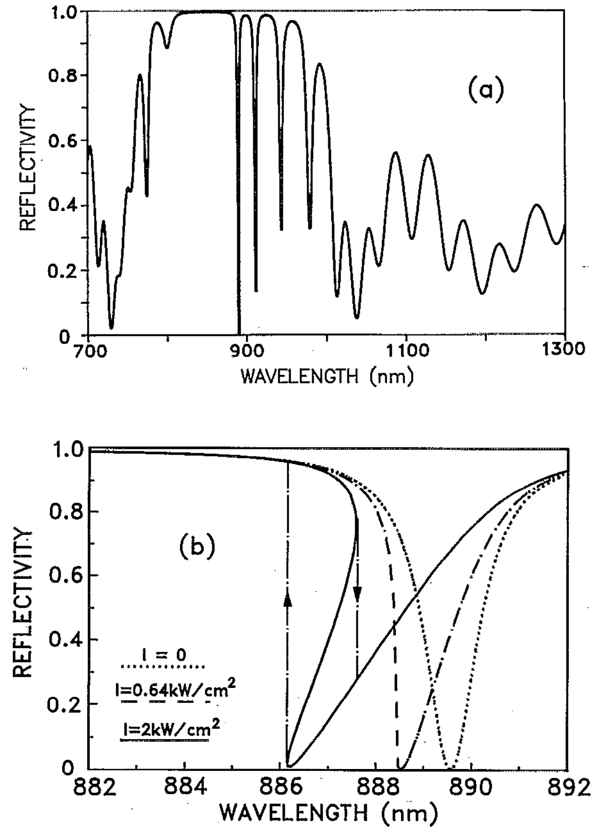

FIG. 1. Linear (a) and nonlinear (b) reflectivity spectra of the combined DFB/FP structure.

Figure 1(b) shows the nonlinear reflectivity spectra in the vicinity of the resonance peak of our interest. The intensity threshold for bistability is found to be 0.64 kW/cm^2, which is over ten times lower than that of a simple DFB structure with a comparable total thickness.[4] For an input intensity of 2 kW/cm^2, the spectrum exhibits a clear multiple-valued feature at the short-wavelength side of the reflectivity peak.

The output-versus-input intensity characteristics of the structure are shown in Fig. 2 for laser wavelengths at 888.4

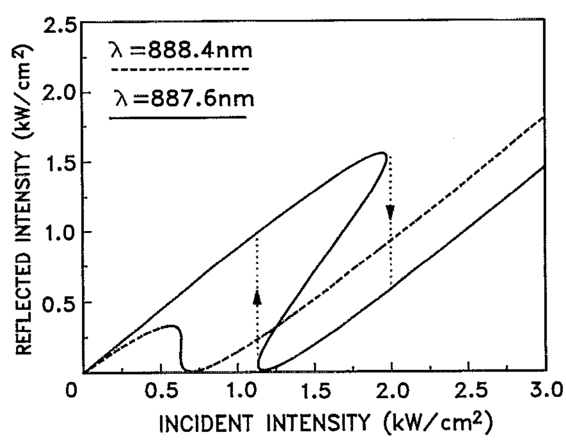

FIG. 2. Reflected-versus-incident intensity characteristics of the structure for two different wavelength detunings.

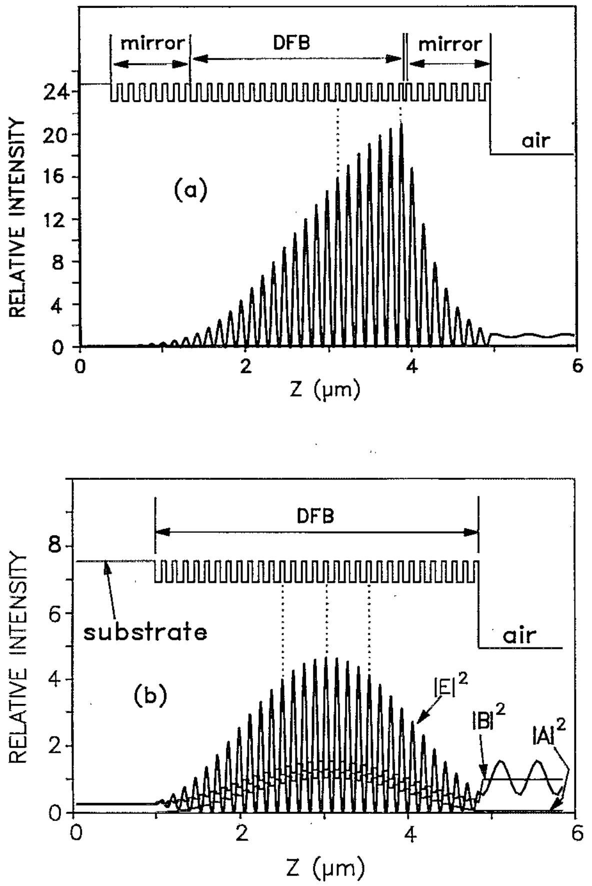

FIG. 3. Intensity distribution in the combined DFB/FP structure (a) and in the DFB structure considered in Ref. 4(b) at resonant wavelengths. The amplitude of the incident beam is normalized to 1. The top curve shows the refractive index profile of the structure. The squared module of the forward and backward wave amplitudes are also shown in (b).

and 887.6 nm, corresponding to detunings of 1.2 and 2 nm from the linear reflectivity peak. The critical detuning for which the bistability just starts to occur is 1.2 nm. With a detuning larger than 1.2 nm, the switching characteristics exhibits a typical bistable hysteresis loop.

The low bistability threshold of the combined DFB/FP structure is due to the double resonance effect which strongly enhances the light intensity in the DFB region. Figure 3(a) shows the intensity distribution in the structure for the linear (low incident intensity) case at the resonance wavelength of 889.6 nm, with the incident intensity normalized to 1. The distribution in a simple DFB structure is shown in Fig. 3(b) for comparison. In addition to the asymmetry in the envelope function, the maximum intensity value is apparently much higher in the combined structure than in the simple DFB structure. Note also that the high intensities are mainly confined in the GaAs layers in both cases. Compared to traditional Fabry–Perot etalons, both structures can maximize the nonlinearity while reducing the overall absorption. This is because the linear nonabsorptive AlAs layers are included in the cavity. While the absorption is related to the amplitudes of the forward and backward waves which change slowly in the structure, the nonlinear refractive index change is proportional to the local intensity which has a strong spatial variation along the z axis.

The contrast and the linewidth of the reflectivity peak as well as the threshold for bistability depend sensitively on the thickness of the phase-matching layer, which had been optimized in the structure considered above. For a phase-matching layer of 110 nm, for example, the reflectivity minimum of the peak of our interest increases to about 74%, which leads to a significant degradation in the nonlinear switching characteristics. The details of the analysis will be published elsewhere.

In conclusion, a combined DFB/FP structure is proposed for optical bistable operations. Using a simple and versatile nonlinear transfer-matrix method, we have demonstrated that the DFB/FP structure can have a much lower bistability threshold than a single DFB structure with a comparable total thickness. The combined structure can also have lower threshold and less sensitivity to absorption than a traditional Fabry–Perot etalon. The phase-matched double resonance mechanism of the structure can also be employed in surface-emitting lasers and other devices. The further optimization of the structure and the experimental investigations are now in progress.

[1] H. M. Gibbs, S. L. McCall, T. N. C. Venkatesan, A. C. Gossard, A. Passner, and W. Wiegmann, Appl. Phys. Lett. **35**, 451 (1979).
[2] D. S. Chemla and D. A. B. Miller, J. Opt. Soc. Am. B **2**, 1155 (1985).
[3] B. G. Sfez, J. L. Oudar, J. C. Michel, R. Kuszelewicz, and R. Azoulay, Appl. Phys. Lett. **57**, 324 (1990).
[4] J. He and M. Cada, IEEE J. Quantum Electron. **QE-27**, 1182 (1991).
[5] M. Cada, J. He, B. Acklin, P. Proctor, D. Martin, F. Morier-Genoud, M.-A. Dupertuis, and J. M. Glinski, Appl. Phys. Let. **60**, 404 (1992).
[6] H. G. Winful, J. H. Marburger, and E. Garmire, Appl. Phys. Lett. **35**, 379 (1979).
[7] W. Chen and D. L. Mills, Phys. Rev. Lett. **58**, 160 (1987).
[8] U. Trutschel and F. Lederer, J. Opt. Soc. Am. B **5**, 2530 (1988).
[9] S. Dutta Gupta, J. Opt. Soc. Am. B **6**, 1927 (1989).
[10] J. Danckaert, K. Fobelets, I. Veterennicoff, G. Vitrant, and R. Reinisch, Phys. Rev. B **44**, 8214 (1991).
[11] H. G. Winful, IEEE J. Quantum Electron. **QE-17**, part II, 164 (1981).
[12] P. K. Milson, A. Miller, and D. C. W. Herbert, Opt. Commun. **69**, 319 (1989).
[13] B. G. Kim and E. Garmire, Opt. Lett. **16**, 1065 (1991).
[14] See, for example, D. A. B. Miller, IEEE J. Quantum Electron. **QE-17**, 306 (1981).
[15] F. Abeles, Ann. Phys. (Paris) **5**, 596 (1950); P. Yeh, A. Yariv, and C. S. Hong, J. Opt. Soc. Am. **67**, 423 (1977).
[16] The wavelength dependence of the material properties are not considered in the calculation because we are only interested in a narrow region near 890 nm.