Optical Bistability in a Nonlinear Thin Film PBG Structure

Liyong Diao and Steve Blair

Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT 84112-9206

Abstract

This paper reports optical bistability in a nonlinear thin film "slow light" structure. This 1-D multi-cavity nonlinear PBG structure can create a significant increase in group delay at the pass-band edge. The group delay enhances the nonlinear phase shift sensitivity. Simulation by a transfer matrix method shows a reduction in bistable threshold intensity by a factor of over 700 in a five cavity PBG structure compared with a single cavity. We also discuss sputter-deposition of SiO_2 thin film and optimal deposition parameters for refractive index, film uniformity and stress.

1. Introduction

Optical bistability means that for an input signal, there are two possibilities for the output signal. To process the input signal correctly, the output signal must also be known, that is, all bistable systems require feedback (e. g. in a resonator)[1]. The first successful experimental demonstration of differential gain and hysteresis[2] was performed by Gibbs et a1 in 1976. Fabry-Perot Interference filters[3] containing a weakly absorbing material, such as ZnSe, have also been shown to have bistable characteristics. The mechanism underlying the large nonlinear refractive effect observed was a thermally induced shift of the semiconductor band gap.

To understand multi-cavity PBG slow light structures, we start by looking at the nonlinear phase shift in a single cavity structure. The intensity buildup in the cavity causes an index change via the optical Kerr effect. The resonant frequency of the structure is then red-shifted, resulting in a nonlinear phase shift for transmitted light. The overall nonlinear phase sensitivity[4] can be written as:

$$\frac{d\Phi}{dI_i} \equiv \frac{2\pi n_2}{\lambda} LS^2 = \frac{2\pi n_2^{eff}}{\lambda} L_{eff}$$

where L is the physical structure length, S is the slowing ratio, L_{eff} is the effective interaction length and n_2^{eff} is the effective Kerr coefficient of the SLS, which can be written as:

$$n_2^{eff} = n_2 S \text{, and } L^{eff} = LS$$

From the above analysis, we find that the slow light structure can enhance the nonlinear phase shift. This suggests that by taking advantage of the slow light nonlinear structure, we can achieve optical bistability with reduced threshold intensity.

2. Bistability in a Nonlinear Thin Film Structure

A single cavity nonlinear Fabry-Perot resonator is made of two highly reflective mirrors and a cavity made of Kerr material. If we replace the idealized mirror with Bragg reflectors made of pairs (P) of quarter-wave layers of high-low index, a single cavity photonic bandgap structure (PBG) is created. As the Bragg reflector alone is highly reflective for a certain band of wavelengths, a band gap is created. The inclusion of a cavity that is made of an integer number (L) of half-wavelengths at the center wavelength of the band gap introduces a pass-band. If we lump several unit cells (N) together, we have a multi-cavity structure, which can enhance nonlinear sensitivity significantly[5]. We denote such a structure as P-L-N, as shown in Fig.1.

The transfer characteristics of this structure can be found by the transfer matrix algorithm[6]. From the plot in Fig. 2, we notice that, for a single cavity structure of 6-16-1, the group delay is only 0.06 ps at 800 nm; for the 6-16-5 structure, however, the maximum group delay is 7 ps at 800.48 nm. In both cases, the transmittance is high at the frequency of maximum group delay. Light intensity can be enhanced significantly.

We input a signal red-detuned from the central resonance at 10% linear transmittance. As the input intensity increases, the resonance red-shifts due to the nonlinear index change. Therefore, the incident frequency becomes more resonant. This positive feedback causes the output to shift from “off” to “on” as shown in Fig 3. The simulation shows a reduction in bistable threshold intensity by a factor of over 700 in a five cavity PBG structure of 6-16-5 compared with a similar single cavity structure of 6-16-1. For the 5-cavity structure, the normalized input light intensity ($n_2 I_{in}$) to achieve bistability is 2.3 $x10^{-6}$; for the single cavity, the normalized input light intensity to achieve bistability is $1.7x10^{-3}$. From here it is evident that for the multicavity structure, the phase sensitivity is enhanced dramatically. From the analysis in the previous section, we know that the reduction in threshold reduction originates from the fact that $d\phi/dI_{in}$ is proportional to S^2.

This design demonstrates the idea of reduced bistable threshold intensity in multi-cavity structures. However, the cavity length is 8 times the wavelength. It will be difficult to fabricate such a thick cavity. So a structure with short cavity is desirable. Based on this motivation, two more combinations of P-L-N are studied. The bistable threshold intensity is listed in Table 1. A reduction of threshold intensity of 1250 is achieved in a 4-4-5 structure, however, the normalized intensity is $1.6x10^{-4}$, which is higher than that of 6-16-5 structure.

3. Fabrication of Thin Film Structure

There are many ways to deposit thin films. Thermal evaporation and RF magnetron sputtering are the most commonly used. The deposition rate of thermal evaporation by electron-beam gun is high, but the quality of the film is relatively poor. Poor uniformity over large areas is another drawback. Ion plating is another promising method but materials for this process must be conducting. Sputtering has been applied to the deposition of optical multilayer coatings for many years. The deposition process is steady and predictable, and the resulting coatings are bulk-like and exhibit no significant aging. However deposition rates are several orders of magnitude lower than those of evaporation. The uniformity over large areas can be controlled by sample rotation. Recently, pulsed DC sputtering has become an attractive method for dielectric films. We report thin film characterization of SiO_2 thin film and optimal deposition parameters for refractive index, film uniformity and stress.

The sputter system is made by T-M Vacuum. The pulsed DC power supply is RPG-100 from ENI. A 3” circular magnetron assembly is made by Angstrom Sciences. A load lock sits on top of the sputter chamber. Both the chamber and the load lock can be pumped down to $5x10^{-6}$ mTorr in 20 minutes with an Edward roughing pump and a cryogenic pump. The wafer can be mounted vertically on one side of an octagonal carrousel. The carrousel can be rotated continuously or in steps of 45°.

The system was not equipped with wafer rotation mechanism initially. The film uniformity on a 2” wafer achieved was about ±3.5%. With customer-designed wafer rotation about the center point of a wafer, the film uniformity achieved is now about ±1% as shown in Table 2. The film thickness, refractive index and loss were measured with a J. A. Woollam Variable-angle Spectroscopic Ellipsometer (VASE).

The optimal sputter deposition parameters were screened by a design of experiment method. There are three significant variables for consideration to achieve best quality film in terms of refractive index, loss and deposition rate. The three variables are argon pressure during deposition, power level and frequency of power source. The effects of argon pressure and frequency variation on film refractive index are shown in Fig. 4 (a) and (b). It can be seen that in the above processing range, as the argon pressure increases, the refractive index change is insignificant. However, as the power level increases, the refractive index increases significantly. From Fig. 4 (c), we notice that the mean of the index is 1.461. It is very close to the bulk SiO_2 refractive index.

Stress in thin films result from thermal expansion (thermal stress) or from microstructure of the deposited film (intrinsic stress). Thermal stress, as implied by its name, is caused by above room temperature deposition. The film so deposited experiences stress due to different thermal expansion coefficient of different materials as the temperature cools down. To understand intrinsic stress of sputtered thin film is a complicated task. There are many models to explain why film stress is tensile or compressive. It is generally accepted that the intrinsic stress is process dependent. It will vary with gas pressure, substrate bias, target/gas mass ratio, substrate, orientation, cathode shape. To take pressure as an example, as the argon pressure increases, the probability for a free radical to collide with argon molecules increases.

The kinetic energy of the free radicals and the sputtered atoms is reduced. So the film deposited at lower pressure tends to be compressive and the film deposited at high pressure tends to be tensile. Our experimental data of stress variation vs. pressure is shown in Fig 5.

4. Conclusions

This paper reports optical bistability in a nonlinear thin film "slow light" structure. This 1-D PBG structure can create a significant increase in group delay at the pass-band edge. The group delay enhances the nonlinear phase shift sensitivity significantly. Simulation by the transfer matrix method shows a reduction in input intensity by a factor of over 700 to achieve optical bistability in a five cavity "slow light" PBG structure compared with a similar single cavity structure. Optical bistability has promising applications in optical computing and optical communication networks. Further, We also report thin film characterization of SiO_2 with respect to the sputter system setup, thin film uniformity, optimal deposition parameters and stress.

2.1 List of Figures:

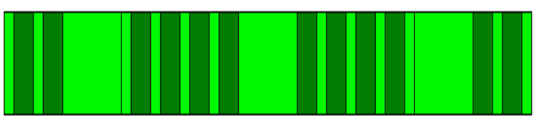
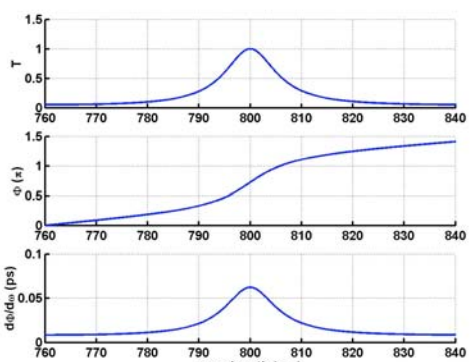
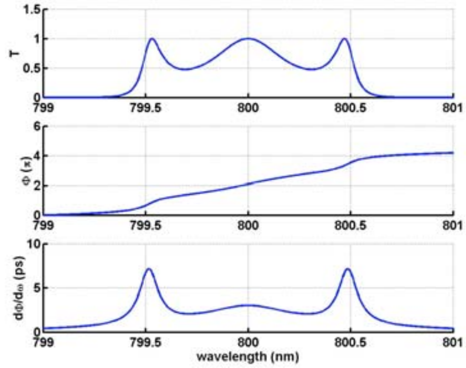


Fig. 1 Multicavity structure of 2-16-3.

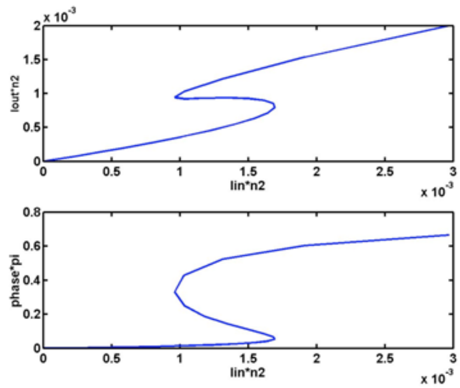


(a)

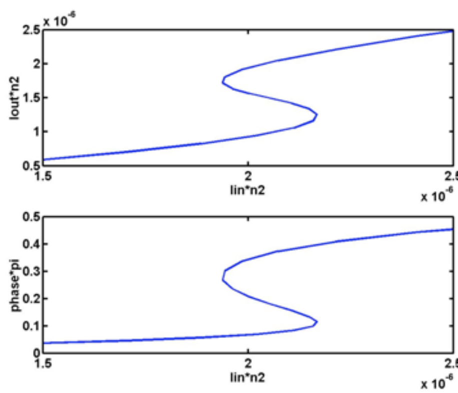


(b)

Fig. 2 Transmittance, phase shift and group delay in single (a) and 5 cavity (b) PBG structure

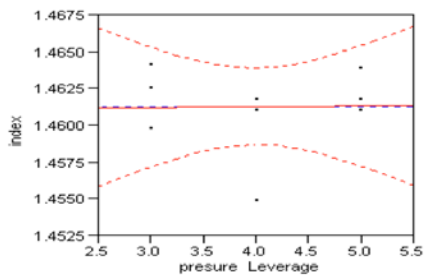


(a)

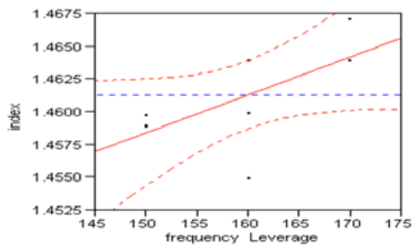


(b)

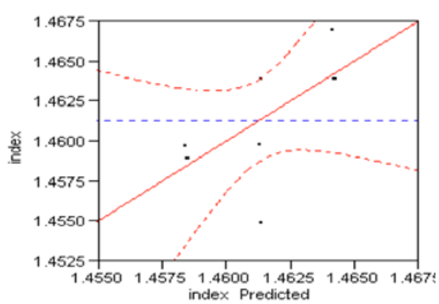
Fig. 3. Bistability in single cavity (a) and 5-cavity (b) PBG structure.



(a)



(b)



(c)

Fig. 4 Effects of argon pressure (a) and frequency (b) variation on SiO_2 refractive index and prediction of refractive index (c)

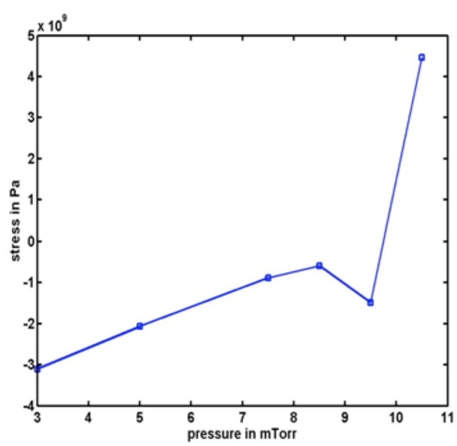


Fig. 5 SiO_2 film stress vs. pressure

2.2 List of tables

	Cavity Number=1	Cavity Number=3	Cavity Number=5
Mirror pair=4 Cavity length=4(λ/2)	0.2	$1.4x10^{-3}$	$1.6x10^{-4}$
Mirror pair=6 Cavity length=4(λ/2)	$6x10^{-3}$	$7x10^{-5}$	$8x10^{-6}$
Mirror pair=6 Cavity length=16(λ/2)	$1.7x10^{-3}$	$2.1x10^{-5}$	$2.3x10^{-6}$

Table 1. normalized bistable threshold intensity

	Center	Left	Right	top	Bottom	Mean (2")	**Variation (2")**
Before	68.37	65.82	67.35	68.5	64.59	66.92	**±3.52%**
After	124.83	124.45	121.20	124.44	122.64	123.51	**±1.07%**

Table 2. film thickness with and without wafer rotation

4. References

[1] H. S. D. Smith, Applied Optics / Vol. 25, No. 10 / 15 May 1986.

[2] H. M. Gibbs, Physical Review Letter, Vol. 36, No. 19, 1976.

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[4] A. Melloni, F. Morichetti, and M. Martinelli Optical and Quantum Electronics 35, 365-379 (2003).

[5] S. Blair, Optics Letters 27, 613-615 (2002).

[6] Macleod, H. A., Thin Film Optical Filters (3rd), Institute of Physics Publishing, 2001.