Optical bistability in a nonlinear photonic crystal waveguide notch filter

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Abstract

Optical bistability occurs when the effects of nonlinear behaviour of materials cause hysteresis in the transmission and reflection of a device. A possible mechanism for this is a strong dependence of the optical intensity on the index of refraction, e.g. in a cavity near resonance. In a 2-dimensional photonic crystal composed of rods of high-index material in air, a waveguide can be created by removing a line of rods. When a cavity is made by taking away several rods perpendicular to the waveguide, a notch filter characteristic in the transmission occurs. Due to the high intensity in the cavity in resonance, nonlinear effects are enhanced. This paper shows numerical simulations of bistability in the transmission and in the field inside the cavity both when a material inside the cavity has third-order (Kerr-type) nonlinear effects, and when the high-index rods themselves are nonlinear.

Introduction

Photonic crystals are a promising class of structures for integration of optical functions on a chip, due to the fact that both the individual elements that perform optical functions and the interconnects can be very small. One of the functions that are needed is all-optical switching, i.e. changing the characteristic of a device by means of changing the intensity of a light beam. This can most easily be achieved if one has a resonant cavity, in which the intensity is much higher than the power that is entered into the system.

This paper studies the bistability that can occur in a nonlinear two-dimensional photonic crystal notch filter [1]. The photonic crystal under study is composed of a square lattice of square high-index rods, with index of refraction 3.4, in air. The lattice constant is 600 nm; the rods are 150 nm wide. This crystal has a bandgap for TM-polarized light (H-field in the plain of calculation) for wavelengths between approximately 1.3 and 1.8 μm. For wavelengths in the bandgap, a waveguide can be created by removing a line of rods. A cavity created by removing 3 extra rods as shown in Figure 1 gives a notch filter response in the transmission. When the system is in resonance, the intensity in the cavity becomes an order of magnitude higher than the incoming power, and transmission goes to zero; all light is reflected back toward the entry waveguide.

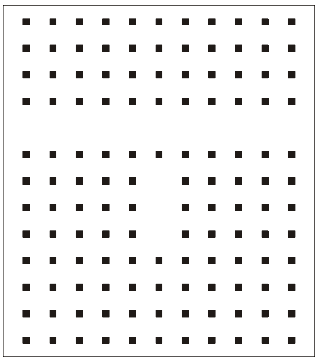

Figure 1: Photonic crystal filter

Introducing Kerr-type nonlinearities into either the high-index rods or the cavity can cause bistable behaviour. We will distinguish a high state and a low state, which are characterized by the amount of energy inside the cavity. This means that the term 'high state' denotes low transmission.

This paper will first shortly describe the numerical algorithm used to simulate the system, then show some results and finish with some concluding remarks.

Numerics

For the calculations, a nonlinear two-dimensional finite difference time domain method is used. It uses a standard implementation of Yee's Mesh [2]. The polarization that is studied is TM; the field vectors are thus $\vec{H} = (H_x, H_y, 0)$ and $\vec{E} = (0, 0, E_z)$. The equations to be solved are:

$$\begin{aligned} &\frac{\partial}{\partial t}\left(\varepsilon_0\varepsilon_r E_z + \varepsilon_0\chi^{(3)}\left|E_z\right|^2 E_z\right) = \frac{\partial}{\partial x}H_y \; \frac{\partial}{\partial y}H_x \\ &\frac{\partial}{\partial t}\mu_0 H_x = \frac{\partial}{\partial y}E_z \\ &\frac{\partial}{\partial t}\mu_0 H_y = -\frac{\partial}{\partial x}E_z \end{aligned} \tag{1}$$

However, having the nonlinear term inside the differentiation with respect to time is difficult to implement numerically. Therefore, the assumption is made that the intensity of the light changes much more slowly than the field, so the intensity can be taken out of the differentiation. After simulations, the validity of this assumption must be checked. The first line of Eq. (1) becomes:

$$\frac{\partial}{\partial t}E_z = \frac{1}{\varepsilon_0\left(\varepsilon_r + \chi^{(3)}\left|E_z\right|^2\right)}\left(\frac{\partial}{\partial x}H_y - \frac{\partial}{\partial y}H_x\right) \tag{2}$$

In each timestep, a predictor-corrector step is used for the intensity to improve stability.

The entire window is surrounded by a Perfectly Matched Layer (PML) [3], which absorbs outgoing radiation. This PML only contains linear materials. In our current implementation, light is launched through the PML by prescribing the field on the outer boundary of the calculation window, ensuring that the light source does not disturb the simulation in the interior of the window.

Results

First, the response of the linear filter is calculated by sending a short pulse down the incoming waveguide and taking the Fourier transform at the exit. This spectrum is then normalized by dividing it by the spectrum of the response of the system without the cavity. The response is given in Figure 2. There is a notch in the transmission at a wavelength of 1520 nm. At this resonance, the intensity inside the cavity is an order of magnitude higher than that in the waveguide. In order to observe optical bistability, the wavelength must be chosen somewhat higher than the notch; λ=1530 nm is chosen.

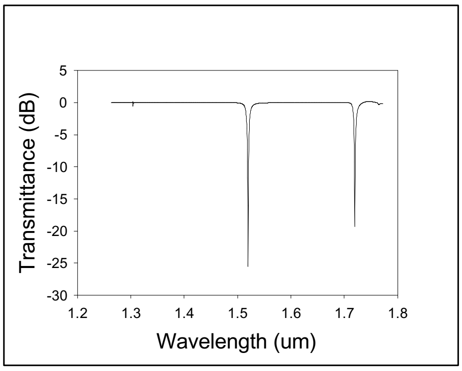

Figure 2: Transmission spectrum of notch filter

First, the high-index rods of the photonic crystal are made nonlinear. $\chi^{(3)}$ is arbitrarily chosen to be 0.08; the powers involved can be scaled accordingly to take into account more realistic materials. The input power is then slowly increased with time, while measuring the intensity at a point in the cavity and at the exit of the waveguide. The power increases linearly for 30 ps until it is $5*10^{-3}$ W/m. It then stays constant for 15 ps, after which it decreases linearly to zero during 30 ps.

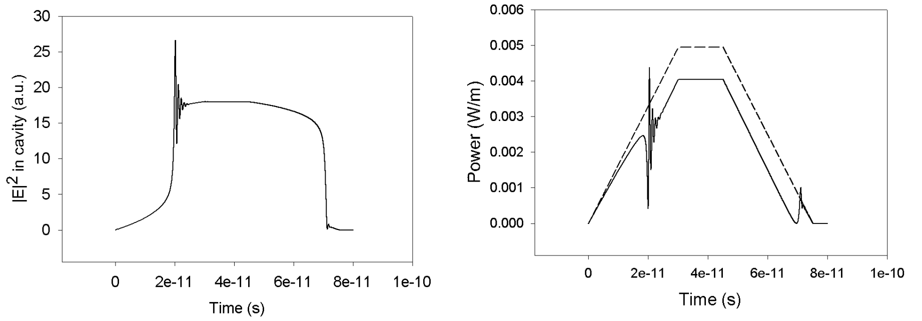

Figure 3: Left: Intensity in the cavity vs. time. Right: Input (dashed) and transmitted (solid) power vs. time.

When the intensity in the cavity increases, the nonlinearity causes the resonance to shift to larger wavelengths. This makes the intensity inside the cavity rise more quickly than the incoming intensity, until the system quickly changes into the high state; see references [4,5]. During this change, the resonance has in fact moved to the other side of the input wavelength. When the input power is then decreased, the resonance shifts back toward the input wavelength, which causes the ratio of the intensity in the cavity to the input power to rise, so the intensity in the cavity remains high for a long time, until the resonance shifts through the input wavelength, and the system flips into the low state. At this moment the system is in resonance, so the output power becomes zero. Figure 3 shows the time evolution of both $|E|^2$ at a point in the cavity and of the transmitted power at the exit waveguide. The intensity varies about 100 times slower than the field itself, so the assumption made in the Numerics section is valid for this system.

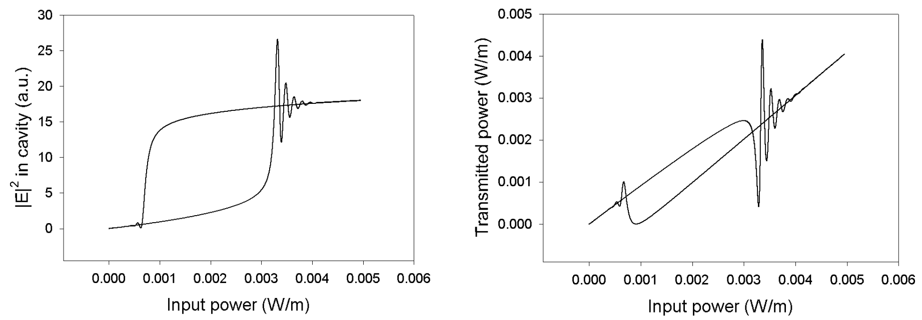

Figure 4: Hysteresis loops of intensity in cavity (left) and transmitted power (right) vs. input power.

In Figure 4, the $|E|^2$ at a point in the cavity and the transmitted power are plotted as a function of the input power. This very clearly shows the hysteresis loops of both the cavity power and the transmission. The cavity power loop runs counterclockwise; the transmission curve is clockwise. Once the high state is reached, the intensity inside the cavity remains at a nearly constant, high value on a large range of input powers; for input powers from about 0.001 to 0.005 W/m the intensity changes only about 15%.

The overshoot and 'ringing', as the oscillations after switching are called, are due to the time it takes for the cavity to fill up; the decay time is directly related to the finesse of the cavity. The frequency of the ringing is proportional to the difference of the eigenfrequency of the cavity and the frequency of the incoming light.

As a different test case, we did not make the high-index rods nonlinear, but the area inside the cavity. The overlap of the fields in the cavity with the nonlinear material is much higher in that case, which causes the switching powers to be about 100 times smaller.

Conclusions

Optically bistable behaviour is possible in a compact photonic crystal filter. For the chosen hypothetical $\chi^{(3)}$ of 0.08 the switching power for the crystal with nonlinear rods is about 0.003 W/m; for real-world materials like AlGaAs ($\chi^{(3)} \sim 10^{-17}$ [6]), this translates to a power of 24 TW/m. If it is possible to restrict the system in the third dimension to 1 µm, this translates into a necessary power of 24 MW.

If a different system, in which the material inside the cavity is nonlinear, this power could be at least two orders of magnitude lower. However, this is not a very realistic system; the cavity in the linear system contains air. A much more realistic, and realizable, system would consist of a different type of photonic crystal: holes of air in a high-index medium, e.g. III-V semiconductor materials. It may be possible to construct a similar type of filter to the one described here, in which the cavity consists of nonlinear material.

The high power requirements probably mean that the system as studied here is not feasible. There are several ways to improve the usability; a first possibility is an increase of the length of the cavity. This will keep the finesse equal, but decrease the free spectral range; thus, the width of the resonance peak will decrease. A smaller width means that a smaller frequency shift is necessary to obtain bistability, and hence lower power. A second way is by increasing the finesse of the cavity directly, e.g. by moving the cavity one rod further away from the waveguide. This has a double effect on the power requirement: One, the resonance linewidth decreases, and two, the ratio of the power in the cavity to the input power becomes much larger. Especially this latter approach is a promising one to investigate further.

Acknowledgements

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