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ENHANCEMENT OF OPTICAL NONLINEARITY IN ONE-DIMENSIONAL PHOTONIC CRYSTALS

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Abstract

Local light intensity at a defect in a photonic crystal structure is greatly enhanced from the input light intensity by the existence of the photonic state localized around the defect. Enhancement of effective optical nonlinearity of photonic crystal structures with a defect which has optical nonlinearity was considered theoretically, and studied experimentally. In experiment, intensity dependence of the transmittance was measured, and reduction of the effective saturation intensity by factor of 20 was observed.

1. Introduction

Control of photon modes by photonic crystal (PC) structures is expected to be a key technology for the future photonic devices. Much attention has been paid to the control of spontaneous emission in PC structures. One of its important goals is a thresholdless laser, which would be available by placing a light-emitting center in a defect in a three-dimensional PC structure, which has three-dimensionally periodical dielectric constant modulation, by microfabrication technology. Our interest, however, is in the utilization of the high local field of the localized photonic state at the defect. Great enhancement of the effective optical nonlinearity of the material at the defect can be achieved by using PC structures. For this purpose, one-dimensional (1-D) structure is the best candidate since the incident field is fully coupled to the local mode only in 1-D structures.

Quarter-wave stacks of two dielectrics with different refractive indices, which have long been used for mirrors or optical filters, are good examples of 1-D PCs. They can have a wide photonic band gap at the frequency where Bragg reflection takes place. By placing a structural defect at the center of the stack, a photonic defect state which is localized around the defect can be made. This defect state induces a sharp transmission peak in the band gap. In fig. 1 is shown the model structure which is dealt with theoretically below. A and B, S, and X designate the two dielectric materials of the periodic structure, the substrate, and the defect layer.

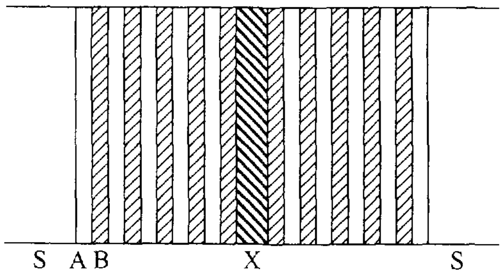

Fig. 1 Structure of the 1-D photonic crystal with a defect.

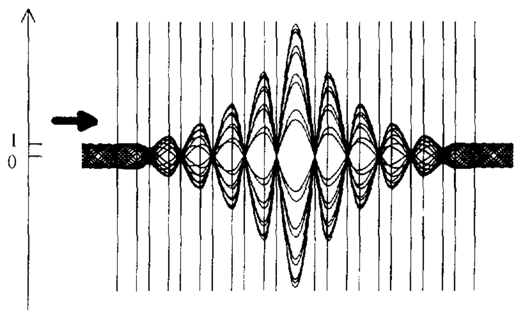

Fig. 2 The field pattern of light at the transmission peak frequency.

In fig. 2, calculated field pattern of light at the transmission peak frequency incident normally on the PC structure is shown. It can be seen from the figure that the local light intensity at the defect is greatly enhanced, which leads to the expectation that the effective optical nonlinearity of the material at the defect layer can be enhanced in such a PC structure.

2. Theoretical

The enhancement of nonlinear absorption in PC structures was first studied theoretically [1]. The materials for A and B are silica and titania, with refractive indices of 1.46 and 2.35, respectively. The defect layer is assumed to have optical nonlinearity, and has finite absorption coefficient. The refractive index of the defect layer is assumed to be 1.5. The substrates are made of glass and the refractive index is assumed to be the same as that of the defect layer. The refractive indices and the layer thicknesses of the periodical part and the defect layer are assumed to satisfy $n_A d_A = n_B d_B = n_X d_X/2$. In this case, the transmission peak appears at the center of the band gap (midgap position). When the thickness of the defect layer is slightly changed from this value, the position of the peak is shifted accordingly. In experiments, the peak wavelength can be tuned using this fact. The transmission spectrum and the local light intensity can be calculated by using the method of characteristic matrices. If all the layers are transparent, the average light intensity in the defect layer at the midgap frequency is enhanced from the input intensity by a factor of $(n_B/n_A)^{2N}/2$. Here N is the number of periods on one side of the defect layers, or $4N + 1$ is the number of layers in the stack. In the case of the model structure shown in fig. 1, $N = 5$. The enhancement of nonlinear transmittance change, in the weak intensity and weak absorption limit, can be shown to be proportional to $(n_B/n_A)^{4N}$. Because for stacks of titania and silica $(n_B/n_A) = 1.6$, nonlinearity enhancement of 10^4 can be expected for a 21-layer stack, and 10^8 for a 41-layer stack.

For samples with finite absorption, the ratio of the average light intensity in the defect layer to the input intensity is greatly suppressed by the absorption in the nonlinear layer, and the (linear) transmittance is also suppressed by the absorption. Since the nonlinear susceptibility for absorption saturation is expected to be proportional to the density of the absorbing dye, *i.e.*, proportional to the absorption coefficient, it can be concluded that the largest absorbance change for fixed number of layers and fixed incident intensity is realized by optimizing the absorption coefficient. Calculations for large N show that the optimized nonlinearity, which is realized for transmittance of about 50 %, is proportional to $(n_B/n_A)^{2N}$. This indicates that enhancement of 100 is expected for a 21-layer stack, and 10^4 for a 41-layer stack. It should be stressed here that this enhancement of nonlinearity can be achieved only by putting the original nonlinear material between two PC structures. Theoretical considerations also show that optical bistability is expected in optically dense samples.

3. Experimental

We fabricated a sample with a nonlinear optical material as a defect in a 1-D PC structure, and studied the nonlinear transmission of the sample experimentally with a nanosecond laser. The defect layer of the sample is a spin-coated polyvinyl alcohol film doped with oxazine 1. This film is placed between two 1-D PCs with the same structure, which are composed of five quarter-wave layers of silica and titania, respectively, as shown in fig. 1. The optical thickness of layer A and B were 640 nm/4. The optical thickness of the defect layer was controlled to tune the transmission peak to the laser wavelength of 620 nm. The extinction coefficient of the defect layer was about 1.4×10^{-3}. The transmittance at the peak wavelength was about 50 %. The transmission spectrum of the sample is shown in fig. 3. For a reference sample, a polyvinyl alcohol film doped with oxazine 1 without PC structure was also prepared. The transmittance of it was controlled to be almost the same as that of the PC sample. Absorption saturation of the sample was measured

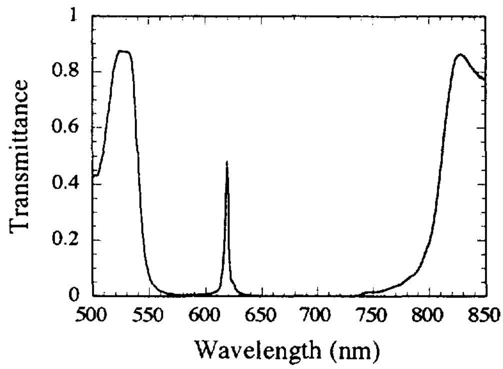

Fig. 3 The transmission spectrum of the PC sample with a defect.

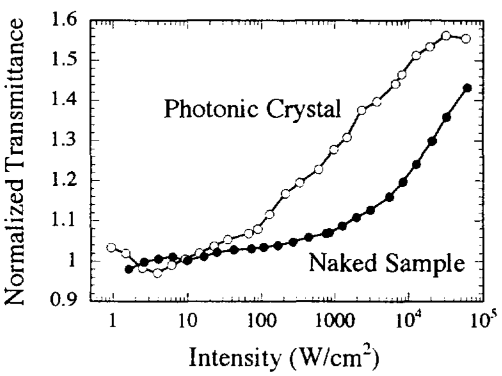

Fig. 4 The input laser intensity dependence of the normalized transmittance of the PC sample and the reference sample over five orders of the input intensity.

by using dye laser pulses. Comparison of the saturation behavior of the films within and without the PC structure over five orders of the input laser intensity is shown in fig. 4. This shows decrease in the effective saturation intensity by factor of 20 in the PC sample, which is consistent with the theoretical consideration.

In summary, enhancement of optical nonlinearity in PC structures with a defect was considered theoretically, and demonstrated experimentally. They can be applied in real photonic devices because of their simple structure and the large enhancement. Getting large signals by optical nonlinearity of other types, such as phase-conjugated wave generation, using PC structures is also a promising application.

1. T. Hattori et al., to be published.