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Research Report

Ultrafast All-Optical Switching: Photonic Engineering of Resonator Structures with Organic Nonlinear Kerr Materials

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A laterally structured all-optical switch based on an optical cavity with high quality factor and an organic nonlinear Kerr material is investigated theoretically. Owing to the non-linearity in the cavity, the resonance shifts in frequency on increase of the pump power, leading to either transmission or blocking of the signal beam. Furthermore, we report ultrafast pump & probe measurements of hybrid 1-D photonic bandgap structures consisting of an inorganic microcavity with an organic Kerr material. By varying the pump beam wavelength across the cavity resonance, we are able to distinguish between the underlying nonlinear absorption and the dispersion necessary for all-optical switching. It turns out that in the spectral region between 780 and 880 nm the nonlinear absorption dominates the signal.

INTRODUCTION

All-optical switching is becoming a key technology for next-generation networks. Switching elements in hybrid organic/inorganic photonic nanostructures could lead to higher channel rates and therefore can become the basis for cost-efficient routing devices. Combining organic films with high Kerr nonlinearity and highly optimized resonant

structures is a promising way to make fast switching with low switching energies feasible. However, the design of the resonator structures has to be optimized, and solid knowledge about the deposition of organic films on structured inorganic substrates, as well as a profound knowledge of the Kerr nonlinearity within the desired spectral range are prerequisite. Therefore, we have studied the nonlinear refractive index, as well as the nonlinear absorption of various organic materials within a microcavity in the desired spectral range. Furthermore, we have theoretically investigated a one-dimensional (1-D) photonic crystal resonator structure consisting of conventional waveguides together with rods of radius 0.2*a* (see Fig.1) and with a defect created by increasing the diameter of the central rod.

DESIGN AND MODELING

We study simple resonator structures such as the one shown in Fig. 1, consisting of silicon waveguides and rods with a refractive index of 3.45 in air computationally by using a finite differential time domain (FDTD) code. The light couples from the left-hand-side waveguide into the resonator in the middle and then out into the right-hand-side conventional waveguide. The resonator structure is a 1-D photonic crystal with a defect that is created by increasing the diameter of the central rod. By changing the size of the defect rod, the properties of the resonator can be tuned.

FIGURE 1
Basic structure of the devices investigated in this paper. The conventional waveguides on the left- and the right-hand side serve as input and output. The resonator is created by increasing the radius of the central rod, forming a defect in a 1-D photonic crystal. The rods have a radius of 0.2*a*, where *a* is the spacing between the rods. The conventional waveguides have a width of 0.4*a*, making them single-moded for the desired wavelength.

We choose a defect radius of 0.58*a* where the defect mode exhibits a dipole symmetry [1]. The defect, together with the two rods separating the defect from the conventional waveguides, creates a resonance centered at a frequency of 0.30569 *c*/*a*. This optimizes the transmission to a maximum value of 0.84. The Q-factor of the resonance is approx. 1000, which increases the interaction with the nonlinear material accordingly, but is not so high that the device becomes too slow (for Q = 1000 the switching time is 0.5 ps). If the material of the defect rod exhibits a Kerr nonlinearity, an optical bistability is created. For such a material the electric flux can be written as

$$D = \varepsilon_0 \left(n^2 + \frac{n^2}{\eta_0} n_2 |E|^2 \right) E \qquad (1)$$

where ε_0 is the electric permittivity of the free space, n the refractive index, η_0 the impedance of free space, n_2 the Kerr coefficient, and E the electric field. The second term in Eq. (1) represents the change of the refractive index due to the electric field intensity. By changing the intensity of a control lightbeam, the resonance frequency is shifted, and therefore, the transmission from the signal input to the signal output can be switched on and off. The signal can operate at different frequencies depending on the shape of the cavity and depending the number and/or the period of the rods.

First we calculate the transmission spectra from the signal input to the signal output for different values of the Kerr nonlinearity. The results are shown in Fig. 2 for five different values of $n\ n_2\ I_{\text{input}}$. Here, I_{input} is the intensity in the input waveguide. By increasing $n\ n_2\ I_{\text{input}}$ the resonance peak shifts to lower frequencies. In order to shift the peak to a frequency at which the linear system has a transmission of 0.084 (10% of the maximum transmission) a $n\ n_2\ I_{\text{input}}$ of 12.6×10^{-5} is needed. For larger $n\ n_2\ I_{\text{input}}$, the shifted peaks become steeper at the lower-frequency side and finally bistability sets in.

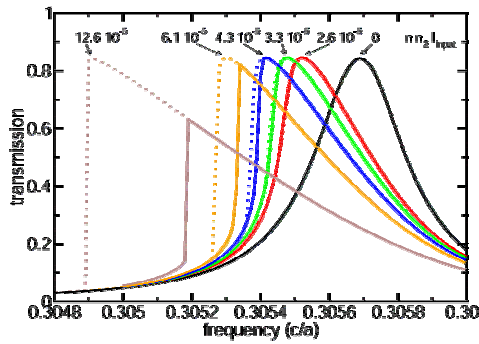

FIGURE 2
The signal output of the all-optical switch versus frequency for five different $n\ n_2\ I_{\text{input}}$ and at a fixed signal input power. The solid lines show the lower hysteresis branches and the dotted ones the upper hysteresis branches of the transmission spectra.

For further investigations we choose $n\ n_2\ I_{\text{input}}$ of 6.1×10^{-5} which is a compromise between two switching levels and the needed nonlinearity. For example, at an input intensity of 200 mW/ μm^2, a Kerr coefficient of 8.8×10^{-17} m^2/W would be necessary to obtain switching. For a fixed frequency and optimum nonlinearity, we then varied the signal input power. The resulting signal output power is displayed in Fig. 3. The signal output power shows a clear switching behavior and a commonly observed hysteresis loop. This behavior already realizes an all-optical switch.

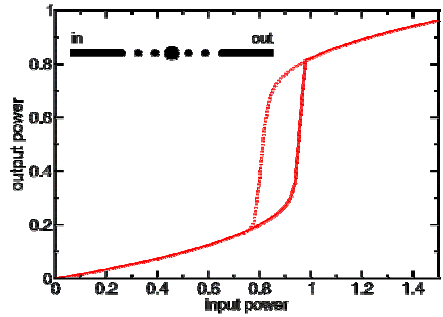

FIGURE 3
Signal input power versus signal output power at an $n\ n_2\ I_{input} = 6.1 \times 10^{-5}$ and a fixed frequency of 0.30534 c/a. The solid line shows the lower hysteresis branch and the dotted line shows the upper hysteresis branch. The inset shows the device structure.

EXPERIMENTAL RESULTS

1-D Fabry-Perot type structures

To select potential nonlinear materials for device applications, we characterized the optical properties of various materials within a cavity with the desired Q-factor. Therefore, we prepared Fabry-Perot (FP) structures by placing the nonlinear material between two quarter-wave stacks. Here, we used either the two-mirror approach (two commercially available mirrors with the organic nonlinear material between them) or the all-in-one-stack approach, in which the second quarter-wave stack is directly prepared on top of the organic material by sputtering or PECVD. Taking into account that in any FP structure the enhancement of the incoming light intensity I_i is proportional to the product of the finesse F and the overall transmission T (on resonance), the best method is to build both reflecting surfaces of the FP as dielectric mirrors that can be highly reflective and have low loss. The imaginary part, as well as the real part, of the susceptibility $\chi^{(3)}$ for the material under investigation was examined through differential transmission measurements. Therefore, we have set up a "fast-scan" pump & probe experiment allowing the characterization of the nonlinear optical properties as well as the temporal behavior of our FP cavities. The main advantage of this system is the use of a fast optical delay (retroreflector mounted on a shaker) for the time delay and the accumulation of the signal with a fast A/D converter without chopping one of the laser beams. Using scan frequencies of up to 150 Hz, i.e. well above the laser noise, extremely high signal-to-noise ratios can be achieved. This could prevent artefacts due to degradation, which are often observed in "ordinary" pump & probe setups. In order to probe the optical properties, we have to ensure that the full width at half maximum (FWHM) of our laser system is narrower than the FWHM of our cavity resonance. Taking into account

that we want to switch on a timescale of a few picoseconds (ps) and that the Q of the cavity should be in the range of 100-1000, we locked our laser system to 2 ps, resulting in a linewidth of approximately 0.5 nm. We defined the linear transmission of our cavities under investigation as $f(\lambda)$. If the pump light leads to a change in the refractive index due to the Kerr nonlinearity of the material and/or to a change in absorption due to nonlinear absorption, the transmission of the cavity at the wavelength λ is changed by $df(\lambda)$. The quantity $df(\lambda)$ is the observable of our pump & probe measurement and is equal to the amplitude of the pump & probe signal. A typical pump & probe signal for a C_{60} cavity is shown in Fig. 4.

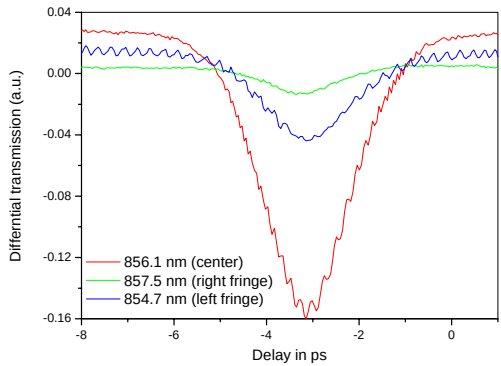

FIGURE 4
Differential transmission of a C_{60} cavity as a function of probe delay at several pump & probe wavelengths.

In our case, the pump-induced change of the probe transmission is small ($df(\lambda) << f(\lambda)$). In this limit $df(\lambda)$ is the sum of two functions, namely g_+ and g_-; g_+ is an even function in λ with respect to the center wavelength of the resonance line (λ_0) and is proportional to α_2, whereas g_- is an odd function in λ with respect to λ_0 and is proportional to n_2:

$$df = g_+ + g_- = \alpha_2 h_+ + n_2 h_- \qquad (2)$$

The functions h_+ (even) and h_- (odd) are completely determined from the linear resonance peak $f(\lambda)$, the intensity of the pump beam and the known cavity parameters, e.g., the order of the resonance, refractive index of the cavity layers etc. Thus, the above equation can be fitted to the experimentally determined $df(\lambda)$ values with α_2 and n_2 as the only fitting parameters. The fit is shown in Fig. 5. The resulting values for α_2 and n_2 regarding their magnitude are in good quantitative agreement with previously reported data by Strohkendl et al. [2]. However, the sign of the n_2 we observe is different. Similar experiments have been conducted with a derivative of poly-*p*-phenylenevinylene (MeH-PPV) as the nonlinear material. Here, degradation and especially linear absorption are

observed which lead to a slow thermal bistability, influencing the experiment and rendering the analysis more difficult.

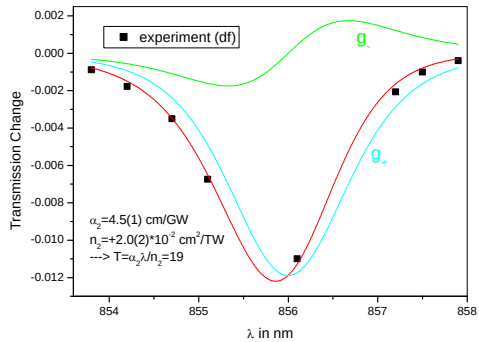

FIGURE 5
Fit (red) through the experimental nonlinear transmission change. The green and the blue curve show the contributions of the nonlinear refractive index and the nonlinear absorption, respectively.

However, the measured pump & probe signals can be analyzed and the α_2 and n_2 values at 782 nm can be estimated:
$\alpha_2 = 0.1$ cm/GW, $n_2 = 0.05$ cm^2/TW, $\rightarrow$ T = 0.16 (a favorable T-figure of merit ($T = \alpha_2\lambda/n_2$)).

In conclusion, we have theoretically investigated a device structure for all-optical switching consisting of ordinary waveguides and rods. We showed that in these structure bistability due to the Kerr nonlinearity of the defect material can be observed. It has been shown that the values needed for the nonlinearity (or control power) are within a range accessible with organic materials. Furthermore, we have investigated the optical properties of different organic materials in the near infrared spectral range. It turns out that MeH-PPV exhibits a promising T-figure of merit, whereas C_{60} is dominated by the nonlinear absorption in this wavelength range.

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