Experiments and modeling of ultra-fast all-optical switching in a GaAs Photonic-Crystal membrane

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***Abstract*— We investigate ultra-fast all-optical switching relying on two-photon-absorption as ruling nonlinear effect in a GaAs Photonic-Crystal membrane. Experiments as well as FDTD modeling provide an unabridged description of such an intriguing nonlinear dynamics.**

Keywords-switch; all-optical switching; photonic crystal; two phton absorption.

I. INTRODUCTION

Over the past years, high-bandwidth (10-100 Gb/s) low-power consumption (few pJ per bit) all-optical signal processing has attracted considerable attention, especially because of its applications within the future ICTs. Meanwhile, 2D photonic crystals (PhCs) are being one of the most promising technologies able to fulfill such high-performance requirements. In fact, by embedding high index material membranes in air, PhCs allow tight confinement and excellent control of the flow of light. Moreover, by exploiting the strong light-matter interaction, PhCs can exacerbate the inherent nonlinear effects of III-V compound semiconductors. This latter feature, in particular, is being an appealing field of study, with remarkable applications in the design of ultra-fast all-optical switching devices [1,2]. From the standpoint of topology, a simple switch could be thought as a resonator coupled to an input and an output waveguide (see inset of Fig. 1 (left)). Such a trivial structure, once driven by means of a high intensity pump, is able to carry a probe signal from the bus to the drop waveguide. The pump signal, by triggering the nonlinear effects inside the cavity, tunes the resonance toward the out-of-resonance probe frequency. This process makes the probe see a sort of bus to drop bridge mediated by the excited cavity, then performing an all-optical switch in (so-called) pump-probe operations. Clearly, performances in switching functionalities are closely related to the structure characteristics. In particular, the pump power required to excite the nonlinear effects inside the cavity has been demonstrated to scale as the V/Q ratio, being Q the quality factor and V the modal volume of the cavity. High Q, small volume PhC nano-cavities supply unmatched values of the Q/V ratio allowing high-performance switching operations [3]. In this work we aim to provide further insights into PhCs switching capabilities both, via experimental demonstration and modeling investigation. In order to address these issues, we first experimentally demonstrate the superiority of PhCs technology in switching difference time domain (FDTD)

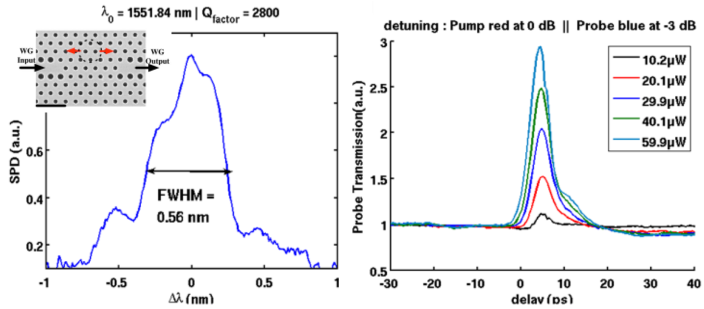

Fig. 1: Spectral response of the GaAs H0 nano-cavity (left) and time-resolved dynamics of the probe transmission (right). Switching is obtained in pump-probe configuration with the pump on resonance and the probe blue-shifted at -3 dB point of the spectral response.

method that, by including the main nonlinear effects of semiconductors, demonstrates capability for predicting the experimental data.

II. EXPERIMENTAL RESULTS

Experiments are performed over a PhC membrane, being the PhC composed by a triangular lattice of air-holes in a GaAs bulk. The topology consists of a H0 cavity coupled to two (input and output) sections of a waveguide, in a in-line configuration [4]. As shown in Fig. 1 (left), the cavity spectral response exhibits a resonance at 1551.84 nm, with a line-width (evaluated as the spectral FWHM) of almost $\Delta\lambda$ = 0.56 nm (Q ~ 2800). Measurements are carried out in non-degenerate pump-probe operations, where the sample is excited via a strong pump signal with carrier frequency at the cavity resonance, and a probe signal blue-detuned by 0.5 nm away from the resonance. The laser emits pump pulses at average power of 100μW and at 36.6 MHz repetition-rate, corresponding to a peak power of 280mW (or average power of 10μW) in the waveguide. To provide the switching efficiency, we use the switching contrast (SC) per required pump power as a figure of merit. The SC is defined as the ratio of the probe power measured at the output waveguide with the pump ON to that with the pump OFF. Fig. 1 (right) shows typical dynamics (in terms of SC vs different input power) as it is expected when the driving nonlinear effect is the two-photon-absorption (TPA), while Kerr nonlinearity and parasitic losses remain negligible. A good SC (1:3) is achieved with relatively low pump power (~60μW), when the probe temporally overlaps (delay equal to zero) the pump while the fast dynamics governed by the carriers relaxation time guarantees high bit-rate transmission.

III. 2D-FDTD Nonlinear Modeling

In order to model the experiments, we set up a full-vectorial time-domain Maxwell's equations solver. The membrane allows for a reasonable description in 2D by using the effective index in the vertical direction and perfect matched layer (PML) absorbing boundary conditions in the plane of PhC. Furthermore, we include in the simulator the master equations accounting for the major nonlinear effects in semiconductors. To provide a best suited model of the nonlinear dynamics, we incorporate the equations accounting for TPA nonlinearity and its related effects. In particular, photon absorption is written as an intensity depletion according to the relation $\partial I/\partial t = -\beta_{TPA} I^2$, where β_{TPA} is the TPA coefficient and I the optical intensity. TPA induced free-carrier-absorption (FCA) is ruled by the equation $\partial I/\partial t = -\sigma_{FCA} N I$, where σ_{FCA} is the cross sections for free-electron and N the free-carrier density. The rate of free carriers generated by photon absorption obeys the following relationship:

$$\frac{\partial N}{\partial t} = \frac{c^2 \varepsilon_0^2 n^2 \beta_{TPA}}{8\hbar\omega_0} I^2 - \frac{N}{\tau} + D\nabla^2 N^2, \qquad (1)$$

being c the speed of light in vacuum, n the unperturbed refractive index, $\hbar$ the Planck constant, ω_0 the carrier frequency, τ the carrier relaxation time and D the diffusion coefficient. The latter term in the right-hand side of Eq. (1) describes the carriers diffusion, i.e. the phenomenon according to which the charges spread as the gradient of their concentration. This causes a shortening of the effective carrier life-time that cannot be thoroughly ignored in PhC based components [5]. Furthermore, we account for the change of the refractive index induced by plasma effect by means of a Drude model [6]. Finally, even though the Kerr nonlinearity is not the ruling effect, it is expected to counteract the TPA contribution. For this reason, self- and cross- phase modulation induced by the refractive index perturbation are included according to the relation $\Delta n = n_2 I^2$, being n_2 the Kerr coefficient. In Fig. 2 are shown the outcomes of the simulations in pump-probe regime versus increasing pump powers. The numerical results show to be in good agreement with the experimental data. As an aside, we numerically evaluate the peak power that enters the structure by calculating the Poynting flux in a section of the input waveguide. In order to do it quite accurately, we define an effective membrane thickness as:

$$h_{eff} = \frac{\left[\int n(r)^2 \,|F(y)|^2 \, dy\right]^2}{\int n(r)^4 \,|F(y)|^4 \, dy}, \qquad (2)$$

where F is the slab mode profile, n the refractive index and y the vertical (perpendicular to the PhC plane) direction. Furthermore, to account for the tight confinement of the resonator, we use the total quality factor Q_{tot} (with $1/Q_{tot} = 1/Q_l + 1/Q_i$, being Q_l and Q_i the loaded and the intrinsic quality factor, respectively).

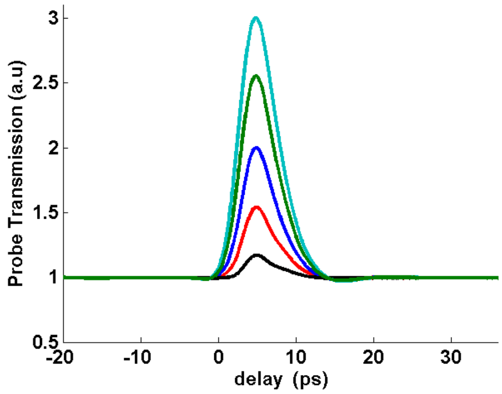

Fig.2: FDTD probe transmission for increasing values of the pump power density in a pump-probe configuration.

The ratio h_{eff}/Q_{tot} give us a reasonable scaling factor for the nonlinear coefficients used in the numerical calculations. In this way, we estimate a threshold power of almost 270mW (black curve in Fig. 2) in excellent agreement with measurements.

IV. Conclusion

In conclusion, we have demonstrated that GaAs PhC based devices are promising switching components. Moreover, by implementing a FDTD approach which account for the nonlinear effects, we have obtained good agreement with the experimental results. Our modified FDTD simulator shows an useful design-tool to investigate more sophisticated switching configurations.

Acknowledgment

The authors acknowledge funding from the EC under the project Copernicus.

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