All-optical signal processing at 10 GHz using a photonic crystal molecule

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We report on 10 GHz operation of an all-optical gate based on an Indium Phosphide Photonic Crystal Molecule. Wavelength conversion and all-optical mixing of microwave signals are demonstrated using the 2 mW output of a mode locked diode laser. The spectral separation of the optical pump and signal is crucial in suppressing optical cross-talk. © 2013 AIP Publishing LLC.

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The strong optical confinement in resonant cavities1 enables energy-efficient and fast all-optical switching. Owing to their very small modal volume, Photonic Crystal (PhC) cavities have enabled nonlinear operation in the sub-femt Joule range and a typical recovery time within a few tens of picoseconds.2 The practical implementation of all-optical switching, frequency conversion, sampling or time-domain demultiplexing requires the suppression of the crosstalk between the control and the data signals. Ensuring a large spectral separation between these is a convenient solution, in particular if polarisation diversity or spatial multiplexing are not possible. In ring cavities, this configuration is readily achieved by assigning the wavelengths of the optical input to different resonances of the resonator comb.1 In photonic crystals, this is achieved with larger, hence, multi-mode cavities.

For instance, optical bistability was demonstrated using a two-mode PhC cavity.3 Kerr-based switching with spectrally separated pump and probe was reported using different Fabry Pérot modes in a PhC waveguide.4 A two-mode cavity capable of spectral and spatial demultiplexing has been shown recently.5

Also, the practical use of optical switches calls for operations at high repetition rates, which implies that thermal effects must be properly handled. A convenient solution involves a solid substrate, acting as an optical isolator and thermal conductor. A recent example relies on the heterogeneous integration of III-V PhC cavities on a silicon photonic chip. This enabled the demonstration of all-optical processing at 10 GHz.6 Here we demonstrate that all-optical processing at high repetition rate is also possible in a device based on air suspended Indium-Phosphide photonic crystal membranes.

We use the concept of photon molecule, namely, the coupling of two single-mode cavities7–9 to generate two supermodes and two resonances. The device is made of a thin (250 nm) membrane of InP grown by Molecular Beam Epitaxy. The hexagonal PhC lattice has a period a = 450 nm and entails two identical HO cavities,10 coupled together (Fig. 1(a)) in a topology similar to that reported recently in Ref. 11. There, the two cavities have slightly different parameters in order to optimize the Fano-assisted switching.12–14 Importantly, only one resonance, entailing the strongly asymmetric lineshape, is involved in the switching operation. Here, instead, the pump and the probe (or, equivalently, the clock and the signal) are assigned to the two resonances. The mutual coupling of the two cavities results into a splitting of about 10 nm (Fig. 1(b)), that is 5 times larger than in Ref. 11 and about an order of magnitude larger than the spectral width of the optical signals (1.2 nm). Therefore, such a large spectral separation enables the efficient suppression of any unwanted cross-talk between the pump and the probe, such that the all-optical switching operation is genuinely due to the nonlinear interaction taking place in the cavity. Also, the choice of two identical cavities maximizes the spatial overlap of the symmetric and anti-symmetric super-modes and thereby the nonlinear interaction.

We note that the input and the output waveguides are directly coupled to both cavities (Fig. 1(a)). This results into a destructive interference between the two resonances and explains the sharp dip observed in the transmission spectrum (Fig. 1(b)). As a result, the maximum static transmission contrast is about 30 dB. This spectral feature is well reproduced by the Coupled Mode Theory (CMT). The overall device transmission, from the input to the output fiber, which includes coupling losses through fiber collimators, microscope objectives, and propagation loss, is approximately 20 dB at the resonance. This has to be compared to about 14 dB overall transmission of a reference waveguide located on the same chip.

The free-carrier induced index change,15 triggered by linear or nonlinear (two-photon, as in the case here) absorption, is the dominant nonlinear process in semiconductor (III-V alloys, specifically) optical microcavities.1,16 We investigated the switching dynamics of the device through two different pump-probe measurements. In both cases, the pump and the probe are obtained by spectral slicing the output of a 100 fs passively mode-locked fiber laser (Optisiv) operating at 36 MHz. The pump (probe) is selected using a 1.2 nm (0.8 nm)
The practical use of an all-optical switch implies operation at fast (>1 GHz) repetition rate. We generate a clock at $f_{\text{MLLD}} = 10.098$ GHz by spectrally slicing the output of a wide band-pass filters, generating pulses approximately 2 ps (3 ps) long. The relative delay is controlled using a mechanical translation stage. We first use a homodyne technique, as in Ref. 17, where the probe is intensity modulated and the signal is detected via a lock-in amplifier. In addition, an Acousto-Optic Modulator shifts in frequency the probe input, while an optical filter (with bandwidth 1 nm) at the output is centered at the probe wavelength, in order to suppress the pump signal.

We then implemented a heterodyne technique equivalent to that in Ref. 18, by replacing the filter at the output with an interferometer connected to the reference pulse and a balanced photodetector. We point out that here the detected signal shown in Fig. 2 is proportional to the probe transmission, as the pump is not chopped and there is no cascaded lock-in. Thus, before the arrival of the pump, the signal is proportional to the linear transmission of the probe pulse.

Fig. 2(a) shows the heterodyne signal as a function of the probe-pump delay, normalized to level in the off state, namely, at negative delay, before the arrival of the pump. The pump is spectrally matched to the resonance at $\approx 1550$ nm, while the probe is blue detuned by 1.4 nm from the resonance at 1560 nm (Fig. 1(b)). The switch-off process clearly reveals two time constants, obtained by fitting the signal with two decaying exponentials. This is consistent with experiments made with InGaAsP and InP PhC cavities, and the two time constants are attributed to carrier diffusion and recombination, respectively.

In all our measurements, the typical value of the fast time constant is about 12 ± 1 ps, while the long time constant is about 200 ps or longer, depending on the excitation level. The switching contrast (on/off ratio of the probe signal) increases with the pump energy and reaches a maximum of about 10 dB. In order to evaluate the switching energy, we assume an input coupling efficiency (including waveguide loss) of about −7 dB. Thus, the average power of 40 $\mu W$ translates into 200 fJ of coupled energy per bit. Conversely, a switching ratio of 5 is achieved with about 100 fJ. We note that the homodyne technique leads to identical (within measurement error) estimates for the switching contrast and decay constants.

The energy per bit figure is well above the sub-femto Joule level demonstrated in GaInAsP PhC, but it is still 2 orders of magnitude better than in micro-ring resonators. It must be noted that the better performances in GaInAsP PhC are entirely due to the much stronger absorption and larger refractive index dependence on the free carrier density of this material. We also note that the two-cavity switch shown here has almost comparable energy performances to the single cavity device made on the same material (InP). The detailed modeling of this single-cavity InP switch, including the heterodyne technique are discussed in a related paper. The switching contrast is related to the linear transmission spectrum (Fig. 1(b)); however, it also depends on the bandwidth of the signal and on the speed of the gate. For instance, from Fig. 1(b) a switching contrast approaching 30 dB would be expected, provided that the signal bandwidth is much narrower and that the nonlinearly induced blue shift of the resonance is made larger than in the experiment reported here.

Besides the switching contrast, the level of the transmitted signal in the on state is also important, as this qualifies the dynamical insertion losses of the device. This is shown in Fig. 2(b), comparing the probe transmission at resonance and when blue-detuned (i.e., configured for switching). Thus, the switch on level reaches about 70% of the probe at resonance.
mode-locked laser diode extending from 1545 to 1555 nm (Alcatel-Lucent-Thales III-V Lab). This is combined with a CW tunable laser to perform a wavelength conversion experiment (Fig. 3(a)). The output is filtered (0.8 nm band-pass filter centered at the CW laser wavelength) in order to reject the pump and then amplified, using an erbium doped fiber amplifier (EDFA) and detected with a fast photodiode ($U_{2t}$, 40 GHz). The pump is tuned at $1550\,\text{nm}$ ($\lambda_1$), while the probe is blue detuned by roughly 1 nm from the resonance at 1560 ($\lambda_2$), e.g., as shown in Fig. 1(a). The exact determination of the effective detuning (i.e., considering a thermally induced drift) is however difficult. In practice, the detuning is set to maximize the all-optical modulation, e.g., the onset of a spectral comb at the output around $\lambda_2$, as shown in Fig. 3(b) (Anritsu, resolution 50 pm). In the time domain (Fig. 3(c)), this corresponds to a peak (about 25 ps) followed by a slower decay, which is consistent with Fig. 2(a). We conclude that this slow time constant does not hinder the fast response, but merely induces a spectral offset of the cavity, provided that the excitation is periodic. The pump average level at input is 2 mW, i.e., 40 fJ per clock pulse. Assuming (based on modeling) that 10% of the coupled energy is absorbed, and a calculated thermal resistance of $1 \times 10^6 \,\text{KW}^{-1}$, we estimate the heating of the cavity to a few Kelvin.

A nonlinear optical switch can be used as an all-optical mixer, where two microwave signals, both on an optical carrier, generate sum and difference frequencies in the optical domain. The implications are that the local oscillator does not need to be close to the mixer and that the isolation of the local oscillator is very good. All-optical mixing (up-conversion) at 40 GHz was demonstrated using Electro Absorption Modulators (EAM). Here we demonstrate the up and down conversion of a microwave signal, with frequency ranging from 0 to 20 GHz, due to mixing with the 10 GHz clock. This is shown in Fig. 4. The device is operated exactly as in the wavelength conversion experiment, except that the CW laser is modulated at $f_{\text{MZ}}$ with a Lithium-Niobate Mach-Zehnder Modulator (20 GHz bandwidth). The optical power of the signal before the device is about 1 mW and the RF driver power is 16 dBm. After filtering the pump ($\lambda_1$) out and optical amplification, the modulated optical carrier is detected and characterized with electrical spectrum analyzer (ESA, Rhode and Schwartz, 40 GHz). The sum and difference of frequencies, $f_s = f_{\text{MLLD}} \pm f_{\text{MZ}}$, are shown in Fig. 4(b), as a result of the all-optical modulation at $f_{\text{MLLD}}$ of the optical carrier modulated at $f_{\text{MZ}}$. The oscilloscope trace of the downconverted signal at $f_s$ (500 MHz) is shown in Fig. 4(c). The dependence of the signal at $f_s$ on the power level of the input at signal at $f_{\text{MZ}}$ is linear, as expected. This is shown in Fig. 4(d). Finally, in order to appreciate the efficiency of the frequency conversion process, we plot the

![FIG. 3. Wavelength conversion experiment at 10.098 GHz. The set-up (a) entails a Mode-Locked Laser Diode, a band-pass filter at 1550 nm, and a tunable CW laser diode set around $\lambda_2 = 1560$ nm. The sample output is either filtered at $\lambda_2$ and detected with a 40 GHz photodiode, or sent to the Optical Spectrum Analyzer (OSA). Oscilloscope trace (b) of the detected signal with average (solid) and (c) spectra of the modulated probe, measured with the OSA revealing modulation at the MLLD frequency.](image)

![FIG. 4. Demonstration of all-optical down-conversion of microwave signals. Experimental set-up including the modulator (a), electrical spectra (b) of the detected optical signal after filtering the pump out; close up near the difference frequency 500 MHz, the MLLD 10.098 GHz, and the MZ driver frequency 10.598 GHz. Corresponding trace at the oscilloscope of the signal at 500 MHz (c). Power, measured at the ESA, of the downconverted signal at $f_s$ vs. the power level of the MZ modulator driver (d) and (e) the same (including $f_s$), as a function of the MZI driver frequency. Here, the power level is relative to the output signal at $f_{\text{MZ}}$.)](image)
electrical power at $f_\pm$ relative to that of the signal modulated at $f_{MZ}$ in Fig. 4(e), e.g., the power levels as shown in Fig. 4(b). The conversion of $f_\pm$ is spectrally flat up to 18 GHz ($-3$ dB). This is consistent with the results in Fig. 3(c). We can attempt a comparison by noting that, while our device is slower than the EAM, still it is operated with a pump power level of 3 dBm only (to be compared with 12 dBm). Moreover, its footprint is orders of magnitude smaller, enabling the easy integration within a monolithic photonic circuit. Besides, speed could be improved by known techniques for accelerating the carrier dynamics. Also, we note that our device is particularly efficient when driven by a mode-locked diode laser, which, by itself, is an excellent clock. This is related to the switching mechanism, namely, the index change following the nonlinear generation of free carriers, which depends strongly on the peak to average power ratio. Therefore, even if the average power level of the optical carrier is as large as that of the clock (namely, our experimental conditions), the switching dynamics is only controlled by the clock, while the response to the signal can still be regarded as linear. This is what is indeed observed in Fig. 4(d). Thus, the signal dynamics is maximized, which is a desirable feature of microwave (i.e., analog) signal processing.

In conclusion, we have designed, fabricated, and demonstrated the all-optical switching operation of an optical gate made of a Photonic Crystal Molecule. This device entails two coupled cavities generating two spectrally well-separated resonances. This configuration is very convenient for practical all-optical switching, as it eliminates any issues related to optical cross-talk between the optical control and the signal. The switching contrast, measured by an optical heterodyne technique, is more than 10 dB with a fast time constant (12 ps). The maximum switching energy (providing the maximum contrast) is 200 fJ. We demonstrate wavelength conversion and all-optical mixing of a microwave signal using only 2 mW of optical power at the waveguide input. The average power coupled in

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