Nonlinear GaInP Photonic Crystal Waveguides

I. Cestier, V. Eckhouse, G. Eisenstein
Electrical Engineering Dept.
Technion
Haifa, Israel

S. Combrié, P. Colman, A. De Rossi
Thales Research and Development
Thales
Palaiseau, France

Abstract — **We report highly nonlinear GaInP photonic crystal waveguides. An extremely large hybrid nonlinearity was demonstrated in a static experiment as well as in a wavelength conversion scheme at 10 Gbit/s. Highly efficient four wave mixing was also demonstrated for either CW or pulsed pump signals.**

Photonic crystyals; Nonlinear optics; Nonlinear wave mixing

I. INTRODUCTION

The small cross section [1] and large group index [2] are responsible for the attractive nonlinear properties of Photonic crystal (PhC) waveguides. Indeed, many nonlinear experiments exploiting mainly the instantaneous Kerr effect have been reported [3-8] in Si, GaAs, AlGaAs, GaInP and chalcogenide glass based PhC structures. Materials with wide band gaps, such as AlGaAs and GaInP are favorable since nonlinear losses [4] are avoided at 1.55 µm so that the effective nonlinearities are enhanced.

In this paper we describe two nonlinear GaInP PhC waveguides. The two waveguides comprise a thin, 170 nm, GaInP free standing membrane into which a triangular lattice of holes was etched. The lattice constant is *a* = 480 nm, the air holes have a radius of *r* = 0.19*a*. The waveguides were 1.3 mm long.

The first device is a low finesse nonlinear Fabry Perot resonator constructed by the ~40% reflectivity of the cleaved end facets. In this device we make use of a hybrid nonlinear phenomenon which combines a thermal effect with the Kerr nonlinearity. The structure enables to extract the phenomenological nonlinear coefficient γ by a direct observation of the phase shift experienced by the Fabry-Perot fringes as a response to an optical pump. A very efficient static response as well as wavelength conversion at 10 Gbit/s was demonstrated. The second device is similar except that it contains mode converters [9] which raise the coupling efficiency and eliminate the end facet reflectivities. This device was used to demonstrate highly efficient four wave mixing (FWM) for CW and for pulsed pump signals with powers in the mW range.

II. NONLINEAR RESONATOR

The nonlinear resonator was characterized using a static pump probe scheme with which the phase shift experienced by the Fabry Perot fringes was observed. In the static experiment, the pump was a low power CW signal and the probe was a broad band, low power ASE signal from an EDFA. The linear transmission (obtained with the pump off) is shown in Fig. 1 (a) as a blue line. The other traces in Fig. 1 (a) show the measured Fabry Perot fringes for different input pump powers. The pump induces a clear red shift in the phase of the Fabry Perot fringes, which increases with power. The largest observed shift is $\varphi = \pi/3$ for a pump power of 800 µW. We quantify the nonlinearity by the common phenomenological nonlinear parameter γ according to the experimentally observed phase shifts. γ is formulated for the cross phase modulation configuration and takes on the large value of $\gamma = 3.5 \times 10^5\ m^{-1}W^{-1}$ for the mode at λ=1537 nm (group velocity V_g ~c/7). The effect of the group velocity in the PhC waveguide is demonstrated by measuring the phase shift values for various pump wavelengths. Fig. 1 (b) shows the wavelength dependence of γ, together with a quadratic fit of the slowdown factor S (dashed curve). Near the band-edge, the nonlinear parameter of the slow guided mode (V_g ~c/15) is enhanced and reaches the high value of $\gamma = 2.2 \times 10^6\ m^{-1}W^{-1}$. These γ values are much larger than those obtained in experiments that rely solely on the Kerr effect [3-5]. This suggests that the observed nonlinearity is due to a hybrid phenomenon of Kerr and some thermal effects.

To evaluate the dynamic properties we performed a wavelength conversion experiment. The pump was externally modulated at 10 Gbit/s and had an average power of 2 mW. The probe was a CW signal of ~1 mW. The probe was filtered

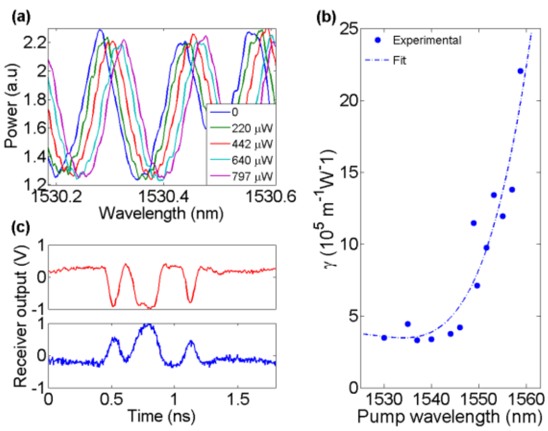

Figure 1. (a) Fabry Perot fringes as a function of wavelength for various input pump powers. (b) γ values as a function of pump wavelength (dots). (c) Pump (red trace) and probe (blue trace) dynamics for a 10 Gbit/s pattern.

at the output following amplification, detected and measured on a fast sampling oscilloscope. Wavelength conversion results are illustrated in Fig. 1 (c). A portion of the data pattern is shown in the case of the probe wavelength with no pump chosen to coincide with a peak of a Fabry Perot fringe. Consequently the converted signal (blue trace) exhibits the complimentary data of the pump (red trace). The probe signal follows the pump pattern very well, proving that even though the thermal effect dominates, the hybrid nonlinearity is sufficiently fast to enable switching at rates of 10 GHz.

III. Non degenerate four wave mixing

For the FWM measurements, the probe was a tunable CW signal while the pump was either a CW or a pulsed signal. In the latter case the pulses were 100 ps wide and had a duty cycle of 1:16. Fig. 2 (a) shows the output spectrum when the pump was pulsed. Pump and probe, detuned here by 1.3 nm, had input power levels of 25 mW (peak) and 1.8 mW, respectively. Two clear first order idler signals are seen. The real levels of the pump and FWM products were 16 times (12 dB) larger than that exhibited due to the averaged detection of the OSA (this is denoted by black arrows in Fig. 2 (a)). The conversion efficiency, defined as the ratio between the output power of the idler on the pump side to the probe input power takes the large value of η = -36 dB. Fig. 2 (b) shows the conversion efficiency dependence on the pump-probe detuning at constant pump and probe levels for a pump wavelength of λ_p = 1550 nm. The experimental data were quantified by a simple model [10]. For co-polarized pump and probe the conversion efficiency is

$$\eta = \gamma P_p(L)(\sinh(gL))^2 e^{-\alpha L}/g \qquad (1)$$

with $P_p(L)$, L, γ , α and g being the average pump power, waveguide length, third order nonlinear coefficient, loss coefficient, and parametric gain respectively. The parametric gain is defined as

$$g = [(\gamma P_p(L))^2 - (\Delta k_L + \Delta k_{NL})/2]^{-1/2}. \qquad (2)$$

The phase mismatch has two contributions: a linear part due to dispersion $\Delta k_L \approx 2\beta_2\Omega^2$ and a nonlinear part $\Delta k_{NL} = \gamma P_p(L)$. β_2 is the linear dispersion and Ω the pump-probe frequency detuning.

The fit shown as a solid line is Fig. 2 (b) matched the measurements very well. The parameters used were a linear dispersion β_2 = -1.47 ps^2/mm (extracted from the linear transmission function of the waveguide), a measured loss coefficient α = 1000 m^{-1}, and a nonlinear coefficient γ = 2900 $m^{-1}W^{-1}$.

IV. CONCLUSIONS

To conclude, we have demonstrated two nonlinear PhC waveguides based on GaInP membranes. One device exhibits an extremely large hybrid nonlinearity which is sufficiently fast to allow for switching at 10 Gbit/s. The second device was used to demonstrate highly efficient FWM for both a CW and a pulsed pump.

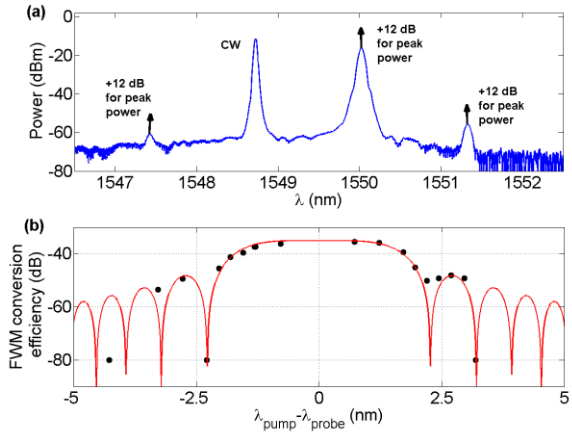

Figure 2. (a) FMW optical spectrum for a CW probe and a modulated pump. (b) FWM efficiency dependence on pump probe detuning for the pump wavelenght of λ_p = 1550 nm (dots). The solid line represents a simulation.

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