Ultra-wide band inter-mode four-wave mixing in sub-wavelength silicon waveguides

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ABSTRACT

We propose an approach to provide wideband inter-mode four-wave mixing independently of the intrinsic dispersion of the involved waveguide modes. Sub-wavelength engineering is adopted to design an effective lateral confinement photonic well, i.e. with a graded potential along the waveguide cross section providing flexible control over the modes' confinement. The self-adaptive nature of the waveguide boundary allows different spatial modes with equi-spaced frequencies and shared propagation wavevector, thus automatically fulfilling both energy conservation and wavevector phase matching conditions. This strategy, which opens a design space for on-chip nonlinear applications, is applied here to silicon waveguides.

Keywords: Silicon photonics, nonlinear optics, four-wave mixing, sub-wavelength structures.

INTRODUCTION

NONLINEAR processes like four-wave mixing (FWM) have a great interest in photonics due to their unique capabilities for on-chip light generation, with especially a large potential for the implementation of wideband sources for silicon photonics [1]-[4]. Harnessing third order nonlinear Kerr effect in silicon already allowed the demonstration of promising frequency combs [5]-[8], optical parametric amplification [9]-[12] and mid-infrared light sources in silicon [13]-[15]. A great effort has been devoted to compensate both the intrinsic material dispersion and the nonlinearity-induced dispersion that can spoil the needed phase matching condition to maximize the efficiency of FWM processes [2]. Nevertheless, achieving broadband phase-matching in fabrication-tolerant silicon waveguides remains a difficult task. The optimization of the transversal dimensions of conventional strip waveguides provided a successful phase-matching approach in relatively narrow wavelength ranges, thus compromising the bandwidth of the nonlinear wavelength conversion processes [9]-[15]. Here, we propose a new strategy to satisfy both phase matching and energy conservation conditions in an ultra-broad wavelength range. Rather than tuning the waveguide dimensions to yield anomalous dispersion, we shape the index profile of the waveguide to support directly different spatial modes with the same propagation constant and equal frequency spacings, ensuring the automatic phase matching and energy conservation rules.

1. PROPOSED APPROACH

In the conventional single-mode FWM approach, depicted in Fig. 1(a), energy is transferred from the pump into signal and idler propagating in the fundamental waveguide mode with different propagation constants. Thus, a precise control of dispersion is required to fulfill phase matching condition ($2k_{zP} = k_{zS} + k_{zI}$). In the proposed multi-mode FWM approach, see Fig.1(b), energy is transferred from the pump into signal and idler propagating in different waveguide modes with the same propagation constant ($k_{zP} = k_{zS} = k_{zI}$). Therefore, the phase matching condition is automatically satisfied. Concurrently, energy conservation requires equal frequency spacing. Then, the bandwidth of the proposed scheme does not depend on the exact dispersion of the waveguide, but on the relative slopes of the dispersion curves of the modes, determining the wavelength range where energy conservation is fulfilled, as illustrated in Fig. 1.

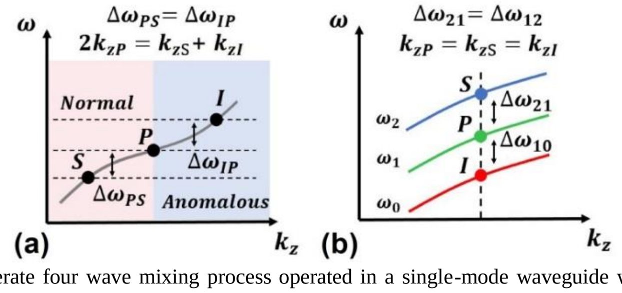

Fig. 1. Description of the degenerate four wave mixing process operated in a single-mode waveguide with anomalous dispersion (a) and operating within an inter-modal scheme regardless the absolute dispersion provided that all dispersion curves are obtained by translating the same curve with a constant frequency step (e.g. $\Delta\omega_{21}$=$\Delta\omega_{10}$ here).

2. OVERVIEW OF THE PROPOSED IMPLEMENTATION

Our concrete implementation of this idea is based on the use of multimode waveguides with a gradual transverse index profile. Our theoretical investigations have led us to identify a very important condition for obtaining multimode guides with constant frequency spacing. It turned out that the effective index of each guided mode of the waveguide should be higher than the index of its edges, so that each mode can freely occupy the desired lateral spacing. This condition, which we have noted Self-Adaptive Boundary (SAB) in Ref [16], combined with subwavelength engineering concepts for the realization of transverse optical index profiles, has allowed the design of various multimode waveguides dedicated to FWM processes.

Fig. 2 shows a typical example designed by considering a 340 nm silicon thick SOI optical wafer. Starting from the concept of a SAB graded index waveguide (3D picture) corresponding to an index profile of the form$(A + By)^p$ after a $2b$ wide central region, with y the waveguide lateral dimension and p a freely adjustable parameter, and thus a graded "potential-like" profile highlighted in Fig. 2 (a), we derived an analytical approach to describe the frequency mode spacing derivative against the mode number m (see Fig. 2 (b)), and checked afterwards the obtained dispersion curves using 3D-FDTD simulation (see Fig. 2 (c)).

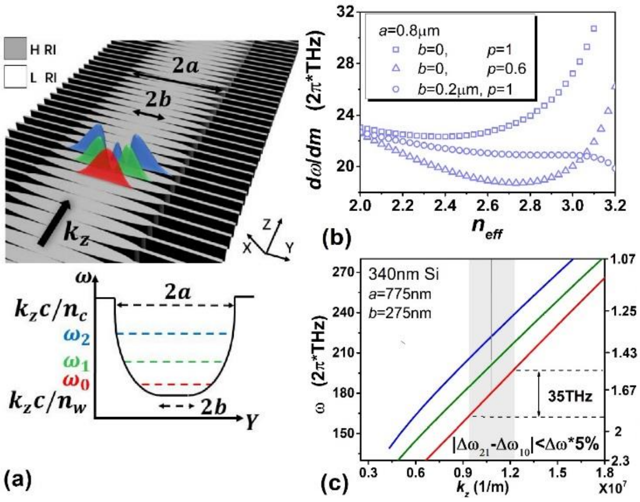

Fig. 2. (a) Sketches of a photonic well described by the cut-off frequency for photon propagating along z axis with wavevector k_z. The unit cells of two types of graded-structure waveguides are presented as well. (b) Analytical Frequency spacings as a function of effective index n_{eff}, with different $orders$ and b values. The other parameters were adopted as: $n_{cent} = 3.48$, $n_b = n_c$=1.8. (c) Frequency spacings as a function of the effective index n_{eff}, using 3D FDTD calculation. The perfect matching point and the 5% tolerant range are labeled by grey line and grey region, respectively.

To take a step back from this whole study, we have studied a large number of waveguide structures, varying the main opto-geometrical parameters of the structures (in particular the thickness of the silicon film in the 200nm-600nm range). These investigations have led us to the conclusion that the proposed approach is quasi-universal, in that we have been able in each case, and without difficulty, to prepare multimode waveguides with very parallel dispersion curves, i.e. directly suited to FWM processes. Simultaneously, inter-modal electric-field overlaps were verified as well by calculating the 3D integral $\frac{\iiint E_{yS}\cdot E_{yP}\cdot E_{yP}^*\cdot E_{yI}^* dr^3}{\iiint |E_{yP}|^2 dr^3 \sqrt{\iiint |E_{yS}|^2 dr^3}\cdot\sqrt{\iiint |E_{yI}|^2 dr^3}}$, which gave values typically around 12%, E_{yS}, $E_{yP}$and E_{yI} corresponding to the field of signal wave, pump wave and idler waves, respectively.

3. CONCLUSION

We report that waveguides with subwavelength-engineered graded index profiles can be designed to support the modes that adapt themselves to different effective boundaries according to their effective index values. This self-adaptive behavior provides a degree of freedom to achieve simultaneous both the energy conservation and phase matching regardless the intrinsic dispersion of the considered optical waveguide modes. This strategy, that can be adapted to different wavelength ranges and material platforms, opens a new design space for the application of FWM processes in multimode optical waveguides. The examples described in this summary will be developed at the conference and complemented by experimental results.

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