Broadband optical parametric amplifier in ultra-compact plasmonic waveguide

Gan Zhou, Tao Wang, Yikai Su

State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, 800 DongChuan Rd, Shanghai Jiao tong University, Shanghai 200240, China

Phone: +(21)34204425, Fax: +(21)34204370, Email: yikaisu@sjtu.edu.cn

Abstract: We propose an ultra-broadband optical parametric amplifier (OPA) employing step-structure hybrid plasmonic waveguide with ultra-high nonlinearity. The proposed parametric amplifier possesses a net signal gain of larger than 14 dB and a 3-dB bandwidth of over 200 nm covering C-band, L-band, and S-band.

1. Introduction

In recent years, the development of silicon optical amplifier is essential for silicon-based photonic integration. Doped fiber amplifiers (DFAs) rely on stimulated emission by doping ions, which operate in a wavelength range determined by the type of doped ions. Raman amplifiers have similar properties, which operate in a bandwidth of tens of nanometer [1]. Optical parametric amplifiers (OPAs) utilize third-order nonlinearity of optical waveguide material, rather than the properties of doped ions. In principle, they can operate at an arbitrary wavelength that fulfills the phase matching for four-wave-mixing. Hence, it is possible to increase the OPA bandwidth that is not achievable with doped-fiber optical amplifiers (DFAs) or Raman amplifier. In this paper, we design a step-structure hybrid plasmonic waveguide which exhibits strong mode confinement and low propagation loss [2], an ultra-broadband optical parametric amplifier is proposed. The obtained operation bandwidth covers C-band, L-band and S-band. To our best knowledge this is the first time that a plasmon waveguide based optical parametric amplifier is proposed.

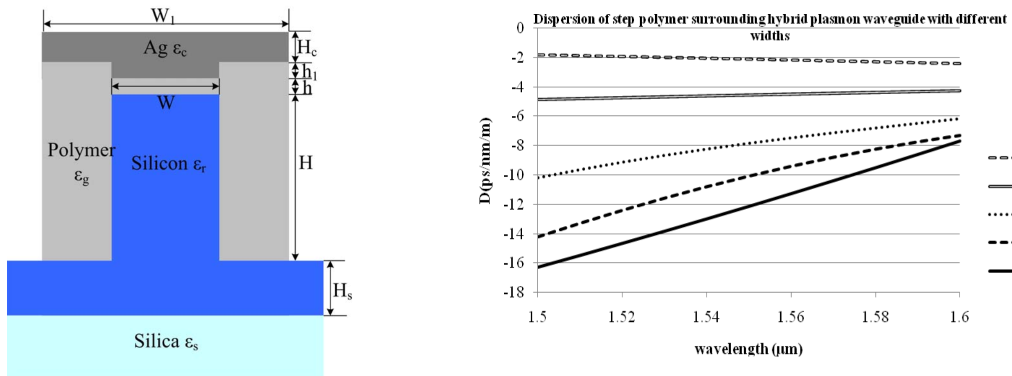
2. **Principles**

OPAs are based on four-wave mixing (FWM) process. Amplification through FWM is a nonlinear optical process derived from the third-order nonlinear susceptibility $\chi^{(3)}$ of a material, which gives rise to an intensity dependent refractive index (IDRI) $n = n_0 + n_2 I$, where n_0 is the linear refractive index, I is the optical intensity, $n_2 = 3Re(\chi^{(3)})/(8n_0)$ is the nonlinear index. A strong pump light and a small-signal light with respective radian frequencies ω_p and ω_s co-propagate in the proposed waveguide. By FWM, two pump photons at frequency ω_p are converted to signal and idler photons at frequencies ω_s and ω_i respectively, leading to amplification of the signal wave. The three waves fulfill the energy conservation: $2\omega_p = \omega_s + \omega_i$ [1]. The parametric gain coefficient g is given by [1]: $g^2 = -\Delta\beta(\Delta\beta/4+\gamma P_0)$, where P_0 is the pump power and $\Delta\beta$ is the linear wave-vector mismatch determined by the waveguide characteristics, i.e., $\Delta\beta = \beta_s + \beta_i - 2\beta_p$, where β_s, β_i, and β_p are respective propagation constants of the signal, the idler and the pump wave. Neglecting the pump depletion, the signal power gain is obtained as [1]: $G_s(L) = (|E_s(L)|/|E_s(0)|)^2 = 1 + [\gamma P_0 \sinh(gL)/g]^2$, where E_s is the signal field, L is the interaction length. For conventional SOI waveguides with $D < 0$, the signal gain occurs over a very narrow band of few nanometers due to the lack of phase-mismatching. For our proposed step-structure hybrid plasmonic waveguide [2] in Fig. 1 (a), the signal gain occurs over a very broad band, due to the ultra-high nonlinearity achieved by its strong mode confinement and high nonlinear polymer as gap layer [2].

3. Simulation results

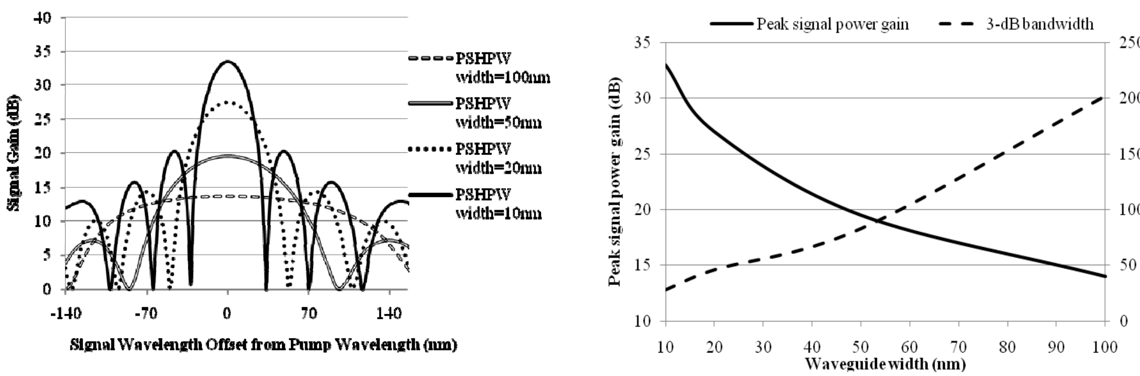
Using the commercial finite-element package FEMLab from COMSOL, the nonlinear coefficients of γ of the step-structure hybrid waveguides with a 20-nm step height and 10 nm, 20 nm, 50 nm and 100 nm silicon ridge widths are 4.7×10^6 W^{-1}m^{-1}, 2.35×10^6 W^{-1}m^{-1}, 9.4×10^5 W^{-1}m^{-1} and 4.7×10^5 W^{-1}m^{-1} [2], respectively. The achieved nonlinear coefficient is more than 3 orders larger than that of conventional silicon waveguide [3]. We plot the GVD for plasmonic waveguides with different cross-sections in Fig. 1 (b). All the waveguides with different widths exhibit normal group-velocity dispersion ($D < 0$). Because the effective index is proportional to the third order of the refractive index of silicon [4], the material dispersion caused by silicon increases. At wavelength near 1.55 μm, silicon shows very large normal group velocity dispersion (GVD) owing to the proximity of the absorption band edge at 1.1 μm [1]. Thus the material dispersion of silicon dominates, leading to a large normal GVD. For larger waveguide width the waveguide dispersion compensates more material dispersion, which makes GVD close to zero.

Based on the ultra-high nonlinearity of step-structure hybrid plasmonic waveguide with different widths [2], Fig. 2 (a) provides the predicted FWM signal gain for a 20-μm waveguide length and a 0.5-W peak pump power using Matlab. With normal GVD, the achievable 3-dB bandwidth of all the waveguide structures is hundreds of nanometer, which is much larger than that of SOI waveguide in [3]. Based on previous equations, the gain bandwidth in terms of $\Delta\beta$ is thus of the order of $4\gamma P_0$. This implies that the larger γ, P_0 or both, the larger is the range of tolerable values of $\Delta\beta$, resulting in that a larger frequency difference between the pump and the signal can be tolerated and thus a larger 3-dB bandwidth. With increasing the waveguide width, the 3-dB bandwidth becomes wider owing to its smaller normal GVD, however, the peak signal gain decreases due to its relatively smaller nonlinear coefficient γ. The achieved signal gains for different waveguide widths are shown in Fig. 2 (b). The achievable broadband optical parametric amplifier exhibits a 14-dB peak signal power gain and 202-nm 3-dB bandwidth covering C-band, L-band and S-band with a waveguide dimension of 100 nm × 5 nm × 20 µm. Compared to optical parametric amplifier based on silicon waveguide [3], this ultra-compact parametric amplifier exhibits ~ 3 times larger 3-dB bandwidth and 5 orders smaller device volume.



(a) (b)

Fig. 1. (a) Schematic of step-structure polymer surrounding hybrid plasmonic waveguide, (b) simulated group-velocity dispersion (GVD), group delay dispersion parameter D versus wavelength with several waveguide cross-section dimensions.



(a) (b)

Fig. 2. (a) Simulated curve of signal power gain and, (b) simulated peak signal power gain and calculated 3-dB bandwidth for step-structure polymer surrounding hybrid plasmonic waveguide with several cross-section dimensions. The signal gain is simulated with a 0.5-W peak pump power at 1550 nm and a 20-µm-long waveguide.

4. Conclusion

In conclusion, we demonstrate a broadband optical parametric amplifier in ultra-compact silicon photonic chip. With a single pump laser of 0.5 W, the optical amplifier is able to amplify and convert wavelengths over 200-nm wide range within the communication bands, and remarkably enhances the optical signal processing capabilities of silicon nano-photonic integrated circuits. This work is supported by NSFC (60777040) and the 863 High-Tech program (2009AA01Z257).

References:

[1] M. E. Marhic, N. Kagi, T. K. Chiang and L. G. Kazovsky, "Broadband fiber optical parametric amplifiers", Opt. Lett. **21**, 573-575 (1996).

[2] G. Zhou, W. Tao, P. Cao, H, Xie, FF. Liu and YK, Su, "Design of Plasmon waveguide with strong field confinement and low loss for nonlinearity enhancement", *accepted at 7th International Conference on Group IV Photonics*, Beijing, China, 1-3 Sept. 2010.

[3] M. A. Foster, M. C. Turner, J. E Sharping, B. S. Schmidt, M. Lipson and A. L. Gaeta, "Broad-band optical parametric gain on a silicon photonic chip", Nature, **441**, 22 (2006).

[4] I. Avrutsky, R. Soref, and W. Buchwald, "Sub-wavelength plasmonic modes in a conductor-gap-dielectric system with a nano-scale gap," Opt. Express, **18**, 348-363 (2010).