

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.

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.

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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, $n_2 = 3\text{Re}(\chi^{(3)})/(\delta n_0)$ 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].

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 $4.7 \times 10^6 \text{ W}^{-1}\text{m}^{-1}$, $2.35 \times 10^6 \text{ W}^{-1}\text{m}^{-1}$, $9.4 \times 10^5 \text{ W}^{-1}\text{m}^{-1}$ and $4.7 \times 10^5 \text{ W}^{-1}\text{m}^{-1}$ [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 $100\text{ nm} \times 5\text{ nm} \times 20\text{ }\mu\text{m}$. 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.

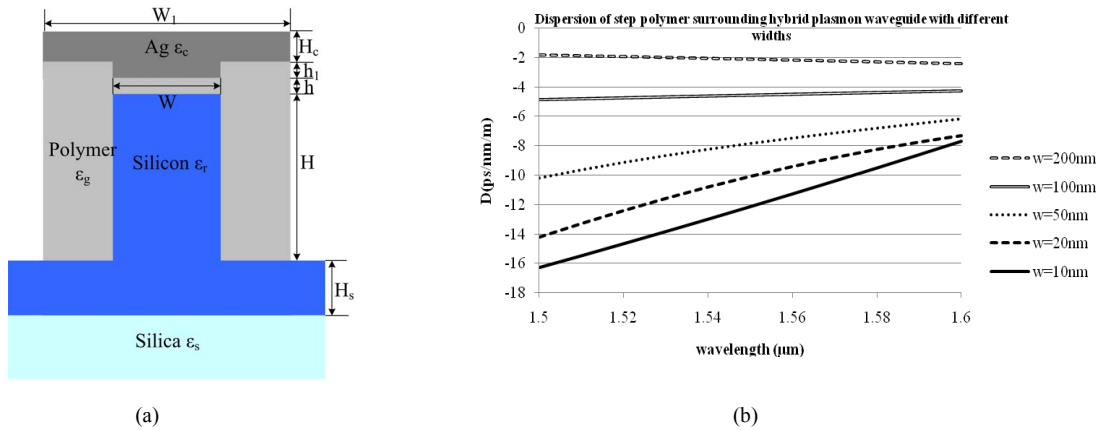


Fig. 1. (a) Schematic of step-structure polymer surrounding hybrid plasmonic waveguide, (b) simulated group-velocity dispersion (GVD), group delay dispersion parameter D versus wavelength with several waveguide cross-section dimensions.

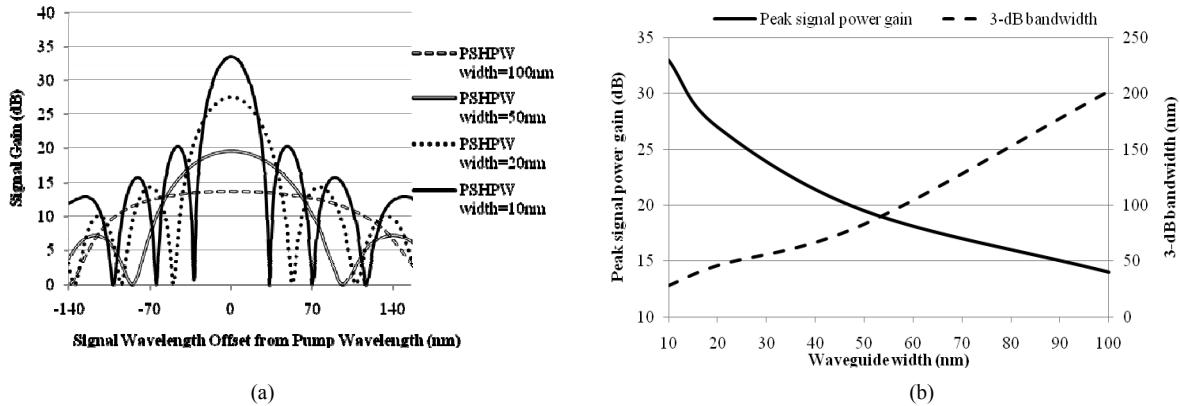


Fig. 2. (a) Simulated curve of signal power gain and, (b) simulated peak signal power gain and calculated 3-dB bandwidth for step-structure polymer surrounding hybrid plasmonic waveguide with several cross-section dimensions. The signal gain is simulated with a 0.5-W peak pump power at 1550 nm and a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

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).

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