Highly-nonlinear ultrafast plasmonic waveguide device on SOI

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Abstract: We propose a step-structure hybrid plasmon waveguide on silicon-on-insulator (SOI). The metal step provides an additional degree of freedom to trade-off between mode confinement and attenuation. The achieved nonlinearity is 2-3 orders larger than that of conventional silicon waveguide. We then design an ultra-compact, broadband optical parametric amplifier (OPA) using such a structure.

1. Introduction

Nanophotonics based on surface plasmon-polaritons (SPPs) are capable of confining lights to nano-scale that is far beyond the diffraction limitation [1, 2]. This unique characteristic enables high density photonic integrated circuits and applications on signal processing with enhanced nonlinearity [1]. However, the applications of SPP are limited due to its high propagation loss caused by the high absorption in metals at telecommunication wavelengths. Thus it is highly desirable to design a plasmonic waveguide with strong field confinement and low propagation loss. For conventional plasmonic waveguides, long-range SPP [1] mode does not exhibit nano-scale field confinement despite its long propagation length, which is not suitable in nano-scale photonic integrated circuits. In recent years, several plasmonic waveguides capable of nano-scale field confinement have been introduced, including wedge waveguide [3], groove waveguide [4], slot waveguide [5], metal nanostrips on a dielectric substrate [6], cylindrical nanowire waveguide [7], and conductor-gap-dielectric (CGD) hybrid-waveguide [8, 9, 10]. Among them, the CGD hybrid waveguide [9] shows better field confinement and lower loss. However the loss increases drastically when the effective mode area scales down to hundreds of square nanometers.

In this paper, we propose a step-structure hybrid plasmonic (SHP) waveguide consisting of silicon, low-index polymer gap, and metal layers. The metal-step height can be tuned to control the conductor-gap-dielectric (CGD) mode in the low-index isolator gap layer. By optimizing the metal step height, the mode size can reach a few nanometers and the propagation length can achieve a few hundred micrometers. Compared to the conventional CGD plasmonic waveguide as shown in Fig. 1 (a), the proposed structure (Fig. 1 (b)) possesses over 40 times higher figure of merit, enabling nano-scale mode confinement and ultra-low propagation loss. By introducing highly-nonlinear polymer as the low-index isolator gap layer, it is a competitive candidate for signal processing based on its ultra-high nonlinearity and high speed response.

Optical parametric amplifiers (OPAs) rely on the third-order nonlinearity of optical waveguide material. In principle, they can operate at an arbitrary wavelength that fulfills the phase matching for four-wave-mixing. The bandwidth depends on pump power, waveguide nonlinearity and dispersion. In this paper, based on the step-structure hybrid plasmonic (SHP) waveguide with strong mode confinement and low propagation loss, an ultra-broadband optical parametric amplifier is proposed utilizing its ultra-high nonlinearity originating from its nanoscale mode confinement and highly nonlinear Region-Regular Poly (3-Hexy1Thiophene) (RR-P3HT) polymer as the gap layer. The obtained operation bandwidth covers C-band, L-band and S-band.

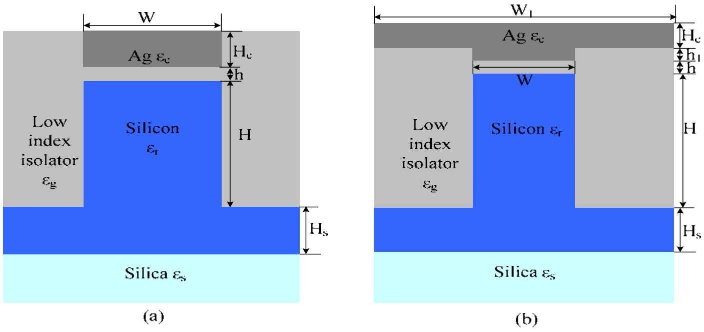

Fig. 1. Schematics of (a) CGD plasmonic waveguide [10], (b) proposed SHP waveguide.

2. Device Structure and Principle

Fig. 1 (a) shows the structure of a conventional CGD plasmonic waveguide with a low-index isolator gap layer instead of SiO2 as introduced in Ref. [10]. Fig. 1 (b) provides the cross section of our proposed SHP waveguide. The SHP waveguide consists of a silicon rib waveguide with a dimension of W×H, a top infinitely-wide Ag-step slab with a step height of h1 and a low-index gap layer. The Ag-step slab is aligned vertically with respect to the silicon rib waveguide but spaced with a low-index gap. The SHP waveguide can be regarded as a combination of two plasmonic waveguides including a silicon ridge surrounding plasmonic (RSP) waveguide with a gap thickness $h_g = h + H + h_1$, and a silicon ridge plasmonic (RP) waveguide with a gap thickness $h_g = h$.

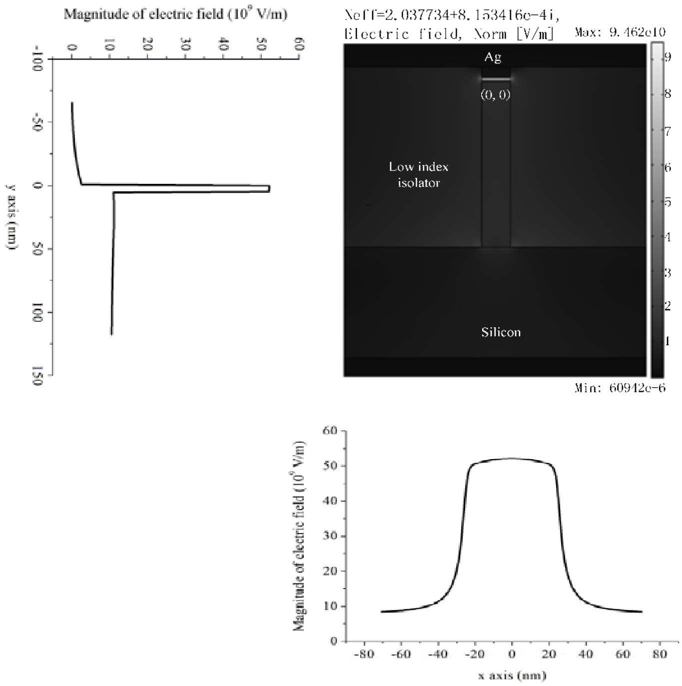

Fig. 2. The norm of the electric field profiles of SHP waveguide in x-y plane; the top left and bottom figures show the norm of electric field at x = 0 and y = 0 respectively. The structural parameters are W = 50 nm, H = 300 nm, h = 5 nm, h1 = 20 nm, Hc = 100 nm, Hs = 200 nm.

The mode profiles are calculated by the finite-element method (FEM) using the commercial mode solver of COMSOL 3.5a. The wavelength λ, is set to 1550 nm in the simulations. The refractive indices of Ag, Si, low-index isolator and SiO_2 are 0.1443 + 11.57i, 3.455, 1.6 (typical for low-index isolator) and 1.455 respectively, corresponding to their dielectric constants of $\varepsilon_c = \varepsilon_{c'} + \varepsilon_{c''} i = -133.75 + 3.34i$, $\varepsilon_r = 11.94$, $\varepsilon_g = 2.56$ and $\varepsilon_s = 2.12$. According to Ref. [9], the CGD mode in the isolator layer remains when h_g is smaller than $h_{g,\,min}$, and releases when h_g is larger than $h_{g,\,min}$. In our proposed waveguide structure, we set h = 5 nm in the middle RP waveguide to obtain a strongly-confined gap mode, and set $h_1 + h + H = 325$ nm (with $h_1 = 20$ nm and H = 300 nm) for the RSP waveguide to reduce the loss compared with the conventional CGD waveguide shown in Fig. 1 (a). Fig. 2 shows the electric field distribution of the SHP waveguide with W = 50 nm, H = 300 nm, h = 5 nm, $h_1 = 20$ nm, Hc = 100 nm, and Hs = 200 nm. It is clearly seen from this figure that the electric field is strongly confined in the h-thickness isolator gap layer in the middle RP waveguide. The calculated effective mode area A_{eff} is 3.01×10^{-4} μm^2, where A_{eff} is defined as the area bounded by the closed 1/e field magnitude contour relative to the global field maximum [11].

3. Optical parametric amplifier

As the electric field is strongly confined in the RP waveguide, one can fill the low-index gap with highly-nonlinear polymer such as RR-P3HT [7]. The achievable nonlinear coefficient γ reaches 1.175×10^8 $W^{-1}km^{-1}$ at 1550 nm, with $\gamma = n_2\omega/(cA_{eff})$, where $n_2 = 2.9\times10^{-17}$ m^2/W is the nonlinear index of the polymer, and c is the light velocity in the vacuum. The propagation distance $L_{prop} = 172$ μm is obtained, which is defined as the distance for the field to decay by a factor of 1/e. The nonlinearity is 2-3 orders higher than conventional silicon (CS) waveguide [12], and the propagation loss is only ten percent of that of the conventional metal/silicon SPP.

Based on this ultra-highly nonlinear plasmonic waveguide, an optical parametric amplifier is introduced. 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 Kerr effect. For our waveguide structure, the effective index is proportional to the third power of the refractive index of silicon, which increase the material dispersion caused by silicon. 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 [13]. 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.

Fig. 3 provides the FWM signal gain for a 20-μm waveguide length and a 0.5-W peak pump power. With normal GVD, the achievable 3-dB bandwidth of all the waveguide structures is hundreds of nanometers, which is much larger than that of SOI waveguide. With the increase of 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 achievable broadband optical parametric amplifier exhibits a 14-dB peak signal power gain and 202-nm gain bandwidth covering C-band, L-band and S-band with a waveguide size of 100 nm x 5 nm x 20 μm.

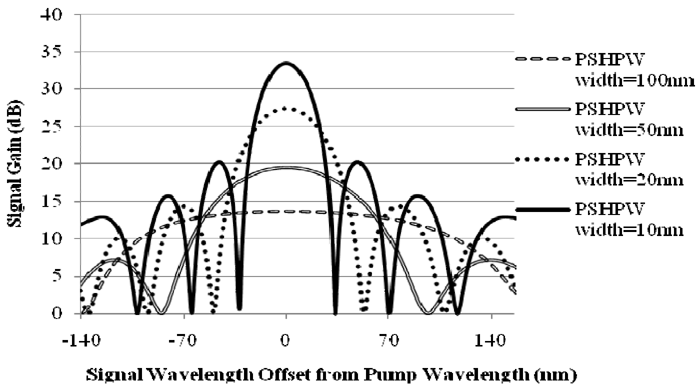

Fig. 3 Simulated curves of signal power gain.

4. Conclusion

In this paper, we propose a step-structure hybrid plasmonic waveguide. Compared to the CGD waveguide, the modal behavior is changed fundamentally by the metal-step height. By optimizing the step height and ridge width, both a nano-scale field confinement and a low propagation loss can be realized. With the proposed waveguide, the light can be confined to an area of $(\lambda/180)^2$ and the loss can be reduced to the 4% of that of the conventional Ag/Si SPP. We also demonstrate a broadband optical parametric amplifier in highly 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 range in the communications bands. This work is supported by NSFC (60777040) and 863 program (2009AA01Z257).

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