Plasmonic Modulator for Three-Dimensional Chip-to-Chip Optical Interconnects

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ABSTRACT

We present a surface-normal plasmonic modulator structure for three-dimensional (3-D) optical interconnects using sub-wavelength metallic photonic crystals. Optical transmission of the metallic slab was controlled by modulating the plasmonic bandgap of the metallic photonic crystal slab with a moderate index perturbation induced by thermo-optic effects. Our experimental results show that more than 60% modulation depth is achieved with only an index modulation of 0.0043.

Keywords: surface plasmons, metallic photonic crystal slab, bandgap, thermo-optic effect

1. INTRODUCTION

The integration of planar-lightwave-circuit (PLC) components with VLSI chips has been intensively investigated nowadays [1-3]. For three-dimensional (3-D) integrated circuits, existing PLC-based optical interconnects are limited due to the factor that only intra-plane photon manipulation can be realized [4-5]. Therefore, surface normal modulator is expected to play an improve role in chip-to-chip optical interconnects. Moreover, existing silico-based photonic modulators are limited by bandwidth due to limited carrier mobility [6]. Plasmonic devices based on metallic photonic crystal slab are suitable when applied as surface-normal modulator, which provide high coupling efficiency, less complexity in fabrication, lower optical loss and expandability with surface-emitting laser arrays for large-scale parallel optical interconnects [7-8]. The discrete guided-modes induced by Bragg-grating-modulated SPPs couple to the broadband Fabry-Perot resonance in the narrow slits, resulting in strong asymmetric Fano resonances with sharp plasmonic bandgaps [9]. In this paper, we successfully demonstrate a surface-normal plasmonic modulator by control the optical transmission. A moderate index perturbation was induced by thermo-optic effects, which results in the shift of the plasmonic bandgap of the metallic photonic crystal slab. The results show that only an index modulation of 0.0043 is required for more than 60% modulation depth.

2. THEORETICAL INVESTIGATION

The proposed structure consists of a one-dimensional array of Au nanowires on top of a glass substrate with refractive index of 1.5023. Figure 1 (a) shows the schematic sketch of the device configuration. The profile parameters of the metallic photonic crystal slab are shown in Fig. 1 (b): the periodicity of the Au grating is p, the thickness of the Au grating is t, and the gap between the adjacent Au nanowires is g. The thickness of glass substrate h is 1.1mm and can be considered as infinite thick in our analysis. The periodicity p=1.032μm, which was designed to excite Bragg-grating-modulated SPPs at the bottom Au-glass surface for surface-normally incident transverse-magnetic (TM) light at 1.55 μm. The gap between the Au nanowire and the Au film thickness were designed both at 100 nm.

The optical transmission in Fig. 2(a) of the grating is simulated by DiffractMod of RsoftTM, which is based on Rigorous Coupled Wave Analysis (RCWA). At the visible and near infrared wavelength range from 400nm to 2μm, we can clearly observe the fundamental and 2nd-order grating-modulated SPPs at both the Au-air and Au-glass surfaces, which possess typical asymmetric lineshape of Fano resonances. From different SPPs modes from the spectrum, it clearly shows that the Q-factor of Au-air SPPs is much higher than that of the Au-glass SPPs, indicating a much longer photon lifetime, which is named as “ridge resonance” in Ref. [10]. However, the sharp transitional edge of the low-Q Au-glass SPPs can still provide the possibility for efficient optical modulation, which is not achievable on a conventional Lorentzian-shape resonance. The optical transmission of the metallic photonic crystals was simulated with index modulation of the glass substrate from 0 to 0.01, within the wavelength range from 1.5 to 1.6μm. Figure 2 (b)

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proves that increasing the refractive index of the glass substrate red-shifts the transmission spectrum. With a probing wavelength of 1552 nm, the simulated optical intensity distribution suggests that a slight index modulation of 0.004 is sufficient to cut off the resonant mode in the metal slits, giving an optical transmission modulation from 5% to 28%.

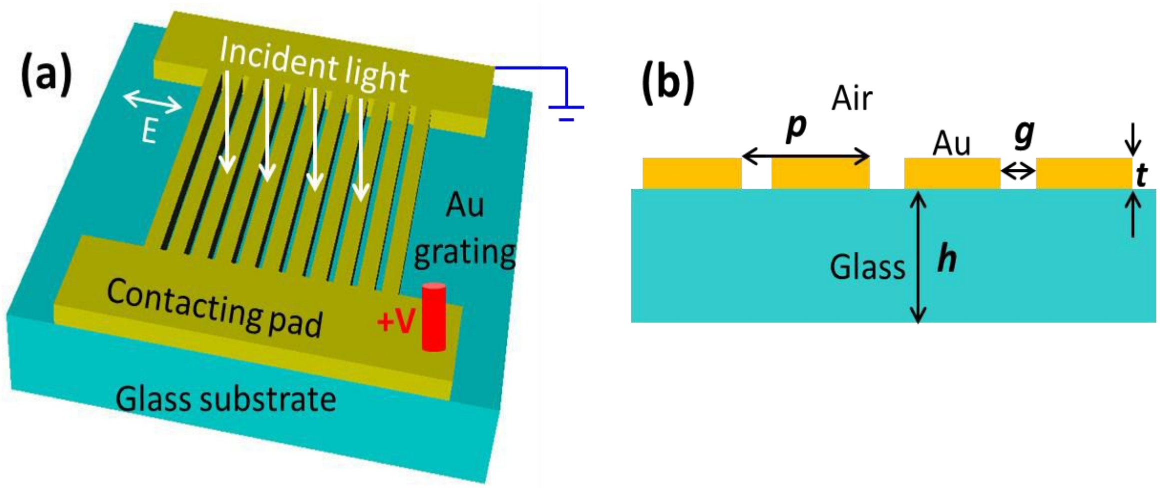

Figure 1. (a) Schematic of the proposed metallic photonic crystals, and (b) Cross sectional view with geometrical parameters

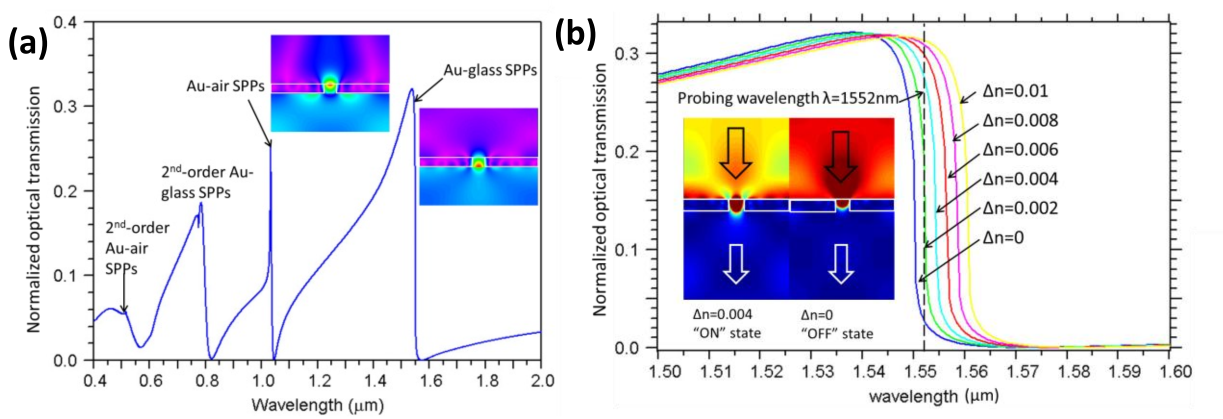

Figure 2. (a) Simulated optical transmission of the metallic photonic crystals at visible and near infrared wavelength; (b) simulated transmission spectrum with different index modulation. The inset figure shows the "ON" and "OFF" state optical intensity distribution of the probing wavelength at 1552nm.

3. EXPERIMENTAL RESULTS

A 100 nm gold thin film was deposited onto Corning 1737 AMLCD glass substrate by thermal evaporation with deposition rate at 8 Å/s. The electrode pads were patterned by conventional photolithography followed by wet etching in gold etchant. The slits are milled using focused-ion beams (FIB), which controlled the width to be 100 nm. The integrated Nanometer Pattern Generation System (NPGS) system was used, which gives periodicity errors less than 0.5% and slit width variation of only 2%.

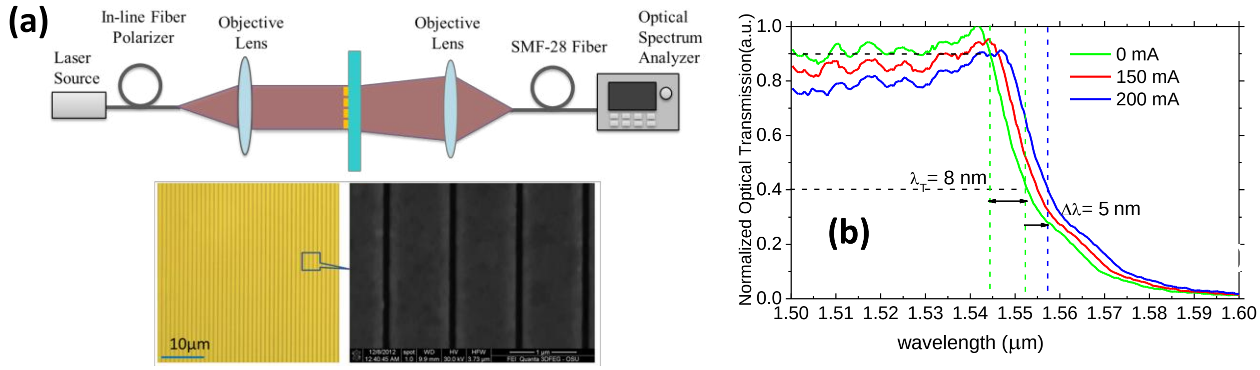

Figure 3. (a) Configuration of the experimental setup used for optical transmission setup. The inset optical microscope and SEM picture show the fabricated metallic photonic crystals (b) Measured transmission spectrum with different heating currents

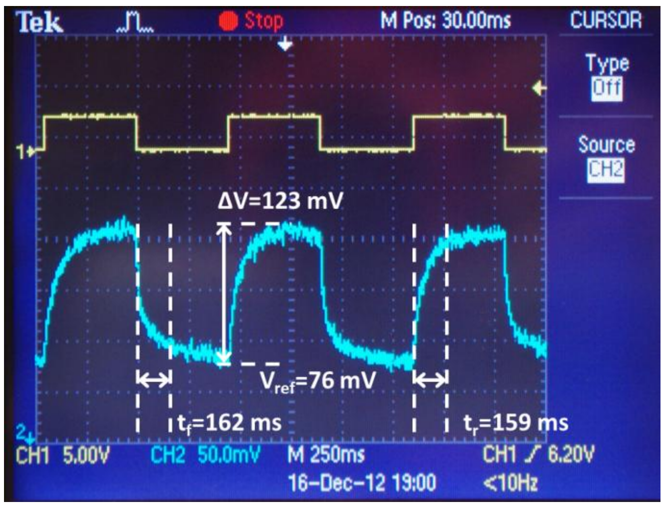

Figure 4. Thermo-optic modulation of the plasmonic bandgap: upper curve is the driving electric signal, and the lower curve is the responding optical signal.

Figure 3(a) shows the experimental setup for the optical transmission measurement of the metallic photonic crystal slab. The inset bottom-left figure shows the optical microscope image of Au nanowire arrays. The scanning electron microscopy (SEM) image in Fig. 3(a) shows zoomed slits. A broadband light source from 1.5-1.6μm wavelength was coupled into a single-mode polarization-maintaining (PM) fiber with an in-line fiber polarizer, resulting in TM polarized light that is perpendicular to the Au nanowire direction. The output light was collimated by a 40× objective lens (NA=0.65). The metallic photonic crystal sample was mounted on a three-dimensional translation/rotation stage, allowing highly precise spatial alignment and angular adjustment with respect to the collimated beam. The transmitted beam after the sample was focused by another 40× objective lens, which was then coupled into a standard SMF-28 fiber and measured by an HP 70951A Optical Spectrum Analyzer. To actively control the optical transmission by thermo-optic effects, the Au contacting pads of the metallic photonic crystal slab were wire-bonded and connected with a DC power supply. A multi-meter was used to measure the current flowing through the device. The total serial resistance is measured to be 3.2 Ω by Agilent 4155C semiconductor parameter analyzer with a Karlsuss PA-200 probe station. The measured transmission spectrum of the metallic photonic crystal slab was shown in Fig. 3 (b). A sharp transitional edge was observed: the relative optical transmission drops from 90% to 40% within only 8nm wavelength. This measurement qualitatively agrees with the simulated results shown in Fig. 2(b). However, the transitional edge is not as sharp as what the numerical simulation predicts, which is possibly due to the fabrication variation and non-perfect beam collimation. A plasmonic photonic bandgap, which is the minimum transmission window, is observed beyond 1.57μm. Figure 3(b) shows the optical spectra when applying currents at 150 mA and 200 mA, respectively. A red shift of the plasmonic resonance occurs when glass substrate is heated due to the current passing through the Au nanowires. The increasing of substrate temperature induces the increase of refractive index, which results in the shift of plasmonic bandgap. Under normal incident, the excitation of SPPs is described by the zero-order relation

$$\lambda_0 = n_{spp} p \quad , \tag{1}$$

where

$$n_{spp} = \mathrm{Re}\left(\sqrt{\frac{\varepsilon_{Au}\varepsilon_d}{\varepsilon_{Au} + \varepsilon_d}}\right) \tag{2}$$

The permittivities of the glass and metal ε_d= 1.50232=2.257, ε_{Au} = −104.5+ 3.68i at = 1550 nm, which give n_{spp}=1.518. Therefore the SPP wavelength is calculated as 1567 nm. Applying 200 mA current induces a shift of 5 nm of the SPP wavelength, which is attributed to the change of refractive index of the glass Δn=0.0043 calculated by Equation (1) and (2), indicating that the glass substrate was heated up to approximately 540 ˚C given that the thermo-optic coefficient is dn/dT=7.9×10-6˚C. Two-dimensional (2D) heat transfer of the system was simulated by Comsol 3.5, which indicated that the substrate was heated to 595 ˚C. The temperature from 2D simulation is slightly higher due to the assumption that the metallic slab has infinitely length. Taking a resistivity of 6.6 μΩ·cm, which is 3× as bulk ρ_{Au} = 2.2 μΩ ·cm, the resistance of the photonic crystal slab region is determined to be about 0.74 Ω. The effective power dissipation of the plasmonic device is around 30 mW. While current was increased to 250 mA, the metallic grating was significantly overheated.

By probing wavelength at 1550nm from a tunable laser, thermal-optical modulation was measured by applying a driven voltage to the device. The device was driven by a square wave (0-3.2V) from a function generator operating at 1.09 Hz, corresponding to heating currents from 0 to 200 mA. The transmitted signal was measured with an InGaAs photodetector, which was connected to an oscilloscope. The electric driving signals and the responding optical signals are shown in Fig. 4, with modulation depth (defined as the induced change in the transmitted optical power normalized to the unperturbed optical output) exceeding 60%. From the modulation measurement, the rising time and falling times were measured to be 159ms and 162ms respectively. This relatively low modulation speed is due to the slow thermal diffusion rate of the glass substrate.

4. CONCLUSION

In conclusion, the plasmonic bandgap of a metallic photonic crystal slab can be efficiently modulated by thermo-optic effects from glass substrate. A sharp transitional edge was formed from transmission spectrum due to the SPPs at Au and glass interfaces. This active control of plasmonic resonance is achieved by engineering the Fano resonance of the metallic photonic crystal. More than 60% modulation depth was obtained with only a moderate index modulation of 0.0043. The power dissipation of the thermo-optic device is around 30mW, which is majorly limited by the low thermo-optic coefficient of the glass substrate. Further improvement will be focused on obtaining a sharper transitional edge, which is favorable for surface-normal electro-optic modulators if using LiNbO3 or nonlinear polymers as the substrates for high-speed modulation. Even smaller index perturbation (Δn~0.001) is required for such electro-optic modulators. Such surface-normal plasmonic modulator can be easily integrated with vertical-surface emitting laser (VCSEL) array, which will provide enormous modulation bandwidth for board level optical interconnects and millimeter-wave photonic systems [11].

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