Design of A Plasmonic Modulator Based on Vanadium Dioxide

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Abstract: ***We present the design of an electrically driven plasmonic modulator that exploits the large refractive index contrast between the metallic and insulating phases of vanadium dioxide to demonstrate high modulation depths in a device with small footprint of 6 um .***

I. Introduction

The modulator is one of the key components required for an optical telecommunication link. A modulator is able to encode a high-speed electronic data stream to an optical carrier wave. Silicon based modulators are widely used in optical communications and can be classified as either resonant or non-resonant[1, 2]. The majority of silicon-based modulators reported so far operate using the plasma dispersion effect in silicon or the Pockels effect in the nonlinear cladding (also known as silicon–organic hybrid (SOH))[2, 3]. Resonant modulators suffer from bandwidth limitations, temperature fluctuations and fabrication tolerances [1, 3, 4]. In contrast, non-resonant modulators operate across a large spectral window and are typically based on a traveling wave configuration. In order to get sufficient modulation depth, there should be long interaction time between the optical and the modulating radio frequency (RF) signal and hence non-resonant modulators are bulky, often up to several millimeters in length. Surface plasmons are surface electromagnetic waves that couple propagating light to charge density oscillations and are confined to the interface between a metal and a dielectric. Plasmonic modulators operating at 40 GHz and 65 GHz have been recently demonstrated in devices with a footprint on the order of 29 μm [1].

Vanadium dioxide (VO_2) is a canonical electro-optic material whose first order insulator to metal transition occurs at temperatures near room temperature (68℃) or adding electric field of $6.5 \times 10^7 V/m$[5]. The phase change of VO2 can happen in picoseconds, which enable the modulator to work at high frequency. Applications of a 3-4 V electric field across an electrode with a nanoscale gap (100 nm) [6] has been reported for photonic switches [7, 8] and optical modulators [5, 8]. The enabling mechanism for many of these devices is utilizing the large refractive index variation of VO2 that accompanies phase change. Here we exploit this element of the phase change to propose a plasmonic modulator to enhance the modulation depth in a small footprint. This approach permits a modulator device footprint of less than 10μm.

II. Device designs and results

Device designs and optimizations were carried out using the finite element method implemented in COMSOL Multiphysics. To demonstrate the optical modulation performance using VO_2, a plasmonic coupling scheme similar to reported in ref [1] was used, which is designed to excite the surface plasmons efficiently by the incident light within C-band wavelength. The refractive indices of VO_2 with respect to wavelength for both semiconductor and metallic phases were experimentally obtained using ellipsometry measurements [9]. Fig. 1 shows our device geometry where the light of wavelength 1550 nm is guided by left silicon waveguide (height 220 nm and width 450 nm) and is coupled to plasmonic slot waveguide (slot width 140 nm) made of gold (thickness 150 nm) through a metal taper. Gold has a good property to excite SPP at visible and IR light wavelength [10]. Light of wavelength 1550 nm is guided by the left silicon waveguide and is coupled through a metal taper to the plasmonic slot waveguide filled with VO_2 in a small section. Semiconductor to metal transition in VO_2 is used to change the phase of surface plasmon polaritons (SPP) by applying a modulating voltage between the gold (Au) electrodes. The information signal has been used as a modulating voltage. A second taper is used to transforms the modulated SPP back to a photonic mode in the right silicon waveguide. This modulator has 2 working states: in the "on" mode, plasmons will propagate along the interface of VO_2 in semi-phase and gold; in the "off" mode, the plasmons will be blocked by the VO_2 in metallic phase with high absorption. Thus, this structure can realize the intensity and phase modulation. The edge coupling scheme has been utilized for coupling the light from the fiber to silicon nanowire.

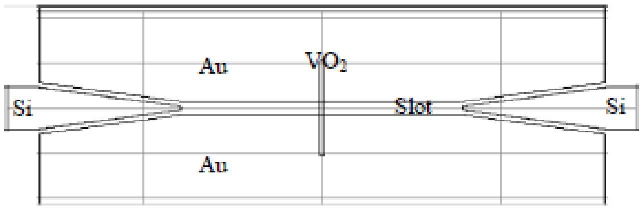

Fig. 1. Schematics of plasmonic modulator using Vanadium dioxide

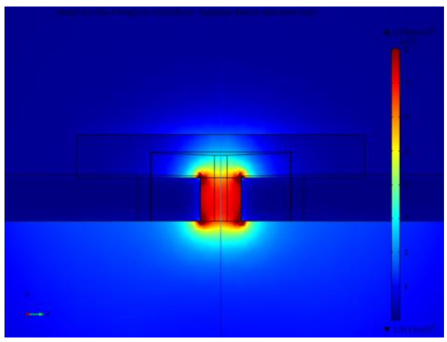

Fig. 2. Cross-sectional view of normalized E-field intensity of surface plasmon confined in the Au-VO_2-Au slot

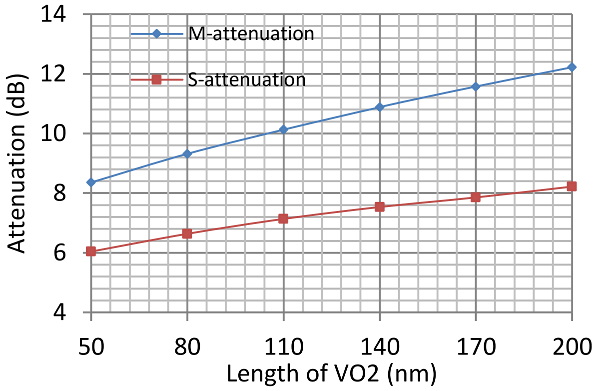

Fig. 3. Simulation results of attenuation of Metallic phase and Semi-phase with respect to length of VO2 slot

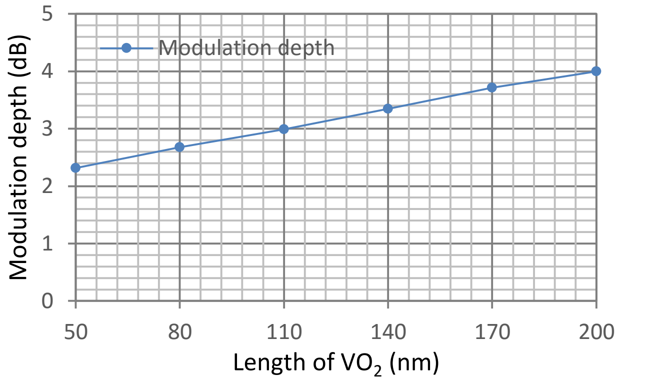

Fig. 4. Variation of modulation depth with the length of VO2 slot

The middle section of the slot was filled with VO_2. The refractive index change accompanying the VO_2 phase change was exploited for optical phase modulation by applying an electric field between the gold electrodes in the slot waveguide. The second taper transforms the modulated surface plasmons back to photonic modes in the right silicon waveguide. Fig. 2 shows the normalized electric field of the surface plasmons confined within the gold-VO_2-gold slot at the cross-sectional cutting plane where VO_2 is in semi-phase.

Fig. 3 shows attenuation of semi-phase and metallic phase of the modulator in dB. We started sweeping the length of VO2 from 50 nm to 200 nm in order to take into account non-uniformities in the film and fabrication tolerances, with an incident light wavelength of 1550 nm. It is observed from our studies that the attenuation of 2 phases and modulation depth increased with increase in the VO_2 length.

Fig. 4 shows the variation of the modulation depth with the length of VO_2.We define the modulation depth as the metallic-phase attenuation subtracting the semi-phase attenuation. Semi-phase attenuation includes the intrinsic loss and insertion loss. The empty slot also has been simulated with incident light from 1400 nm to 1600 nm, which results have been taken as the intrinsic loss of the slot structure.

After considering the insertion loss, modulation depth, fabrication difficulty and modulation voltage, we manage to find a trade-off that the VO2 film length between 80 nm and 170 nm is desirable for the proposed modulator geometry. In current simulation, 200nm-length VO_2 slot only occupied 6.5% of whole plasmonic slot. The modulation depth can be increased by reducing the length of the plasmonic slot.

We have also swept the wavelength of incident light from 1400 nm to 1600 nm with VO_2 film length from 80nm to 170nm length. The results suggest the modulator has a broadband wavelength performance (more than 200 nm) at C-band.

The future work includes utilizing this taper coupling structure to explore the other modulation materials and the comparison of silver and gold plasmonic slot for exciting SPPs.

III. Conclusion

We have presented a plasmonic modulator design based on VO_2, which is feasible to fabricate. The refractive index of VO_2 in the modulator is varied to route surface plasmons through either the low-loss insulating phase or high-loss metallic phase and hence to obtain low insertion loss and high modulation depth in a small footprint. Our modulator design contributes to realizing fully-integrated nanophotonic-nanoelectronic modulators in next-generation high-frequency optical communication technologies.

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