Ultra-compact on-chip metaline based 1.3/1.6 μm wavelength demultiplexer

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In this article, we report an experimental demonstration of enabling technology exploiting resonant properties of plasmonic nanoparticles, for the realization of wavelength sensitive ultra-minutuarized ($4 \times 4 \mu\text{m}$) optical metadevices. To this end the example of a 1.3/1.6 μm wavelength demultiplexer is considered. Its technological implementation is based on the integration of gold cut wire based metalines on the top of a silicon on insulator waveguide. The plasmonic metalines modify locally the effective index of the Si waveguide and thus allow for the implementation of wavelength dependent optical pathways. The 1.3/1.6 μm wavelength separation with extinction ratio between two demultiplexer's channels reaching up to 20dB is experimentally demonstrated. The considered approach, which can be readily adapted to other planar lightwave circuits platforms and nanoresonators of different types of materials, is suited for the implementation of a generic family of wavelength sensitive guided wave optical metadevices.

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1. INTRODUCTION

The continuous improvement of fabrication technologies was the main driving vector enabling miniaturization of electronic circuits components to a nanometers scale. Similar trends hold also for optical circuits, with many efforts devoted to bridge the gap between photonics and electronics. Because of their massless nature, photons are orders of magnitude less confined than electrons. Even in the case of high index materials, such as silicon, implementation of optical functions exploiting interference between co- or contra-propagating waves in nanostructured dielectric materials like photonic crystals [1,2] or similar [3] requires an interaction length of at least several wavelengths.

The change of paradigm brought by the advent of metasurfaces made possible to control the phase and amplitude of reflected or transmitted wave on a “skin depth” propagation length of the order of $\lambda/10$ [4-8]. Based on this approach, numbers of functionalities targeting flat optics applications, have been demonstrated [4-15]. Meanwhile another possibility for the manipulation of the optical flow by means of metasurfaces is to use them in a guided wave configuration [16-22]. The demonstration of a gradient effective index metalens based on this concept was recently reported [23]. The technological implementation is performed by means of a metasurface made of 2D array of gold cut wires (CWs) integrated on the top of the Si waveguide. The aim of the present work is to provide a further impetus

to this direction by introducing the concept of the wavelength dependent optical pathways, distinctly different from the wavelength dependent angular beam steering effects in photonic crystals [24,25] or bi-directional coupling using plasmonic Fano nanoantennas [26]. To prove the feasibility of the considered approach we report the design, fabrication, and experimental demonstration of an ultra-compact ($4 \times 4 \mu\text{m}$) demultiplexer (DMUX) operating in the wavelength range 1.3/1.6 μm .

2. METALINES BASED WAVELENGTH DMUX OPERATION PRINCIPLE, DESIGN AND MODELING

The operation principle of the reported wavelength DMUX is based on the wavelength dependent local variation of the hybrid metal-dielectric waveguide effective index (n_{eff}) induced by the plasmonic nanoresonators. Here we use metalines made of 1D arrays of gold cut wires (CWs) instead of 2D metasurfaces to modify locally the index of a Si waveguide, creating thus the equivalent of color sensitive optical fibers into the Si layer. They can serve as building blocks for numbers of guided wave optical metadevices based on the local variation of the effective index.

The schematic of the hybrid metal-dielectric DMUX operating in a guided wave configuration is shown in Fig. 1(a). Its technological implementation is performed by means of integration of 1D arrays of plasmonic nanoresonators on the top of the 220nm thick silicon on insulator (SOI) slab. The dimensions of gold CWs plasmonic

nanoresonators are adapted to the transmitted wavelengths, around $1.3\mu\text{m}$ in one arm and $1.6\mu\text{m}$ in the other one. DMUX operation is performed in the fundamental TE polarization mode of SOI waveguide, i.e. when the direction of the electric field is parallel to the long axis of CWs in order to induce the excitation of localized surface plasmons.

Fig. 1. (a) Schematic of integrated hybrid plasmonic-photonic wavelength DMUX. The difference in CWs' functional role evidenced by color. (b) Frequency dependence of effective refractive index of the hybrid plasmonic-photonic waveguide for different values of CWs length: 140, 190 and 220 nm considered here.

The resonant frequency of the localized surface plasmons is the primary parameter for the engineering of such hybrid waveguides local effective index. The effective permittivity ϵ_{eff} of the hybrid metal/dielectric slab waveguide can be approximated as the sum of the effective permittivity of the dielectric slab waveguide and Lorentzian type dispersion formula accounting for the resonant features of plasmonic cut wires [22,23]. As shown in Fig. 1(b) the effective refractive index is higher than that of the dielectric slab below the resonant frequency and lower above it. The local value of n_{eff} can thus be on demand engineered through an appropriate design of resonant elements' geometry and their spatial positioning on the surface of slab waveguide. Since the resonant frequency of localized surface plasmons is strongly dependent of their dielectric environment, the use of 5nm thick interfacial native silicon dioxide layer greatly contributes for increasing CWs' resonant frequency and facilitates thus the technological fabrication process [22]. However around the resonance frequency of the gold cut wire occurs a peak of losses. To avoid the detrimental effects of losses inherent to the resonant absorption of metal CWs, it is preferable to detune the operation frequency from the resonance and find an optimal trade-off between index variation and loss.

In the present design the dimensions of CWs used for $1.3\mu\text{m}$ and $1.6\mu\text{m}$ output arms are $140 \times 50 \times 50$ nm [arm 1 in the Fig. 1(a)] and

$190 \times 50 \times 50$ nm [arm 2 in the Fig. 1(a)], respectively. The longitudinal separation distance s between the cut wires in the direction of wave propagation is 50nm for the input area metaline and the output arms 1 and 2. While concerning the transverse separation distance d , it was fixed to 100nm. For a given CWs dimensions the effective index of the hybrid metal-dielectric waveguides, displayed in Fig. 1(b), was determined by means of numerical modeling with subsequent retrieval procedure [23,27]. Here for 140 and 190 nm CWs length the resonance frequencies are 295 THz and 225 THz, respectively.

The role of the additionally implemented $220 \times 50 \times 50$ nm size CWs, with a resonant frequency around 195THz, is to enhance the mode confinement of hybrid plasmonic-photonic waveguide at high frequencies. Indeed, as evident from Fig. 1(b), at the operating frequency of 230THz that corresponds to $1.3\mu\text{m}$ wavelength, the effective index of confinement areas ($n_{\text{conf}}=2.8$) is lower than that of Si slab ($n_{\text{Si slab}}=2.92$), and than that of the arm 1 ($n_{\text{arm 1}}=3.1$). In addition, the frequency of 230THz falls in the highly lossy frequency band of the arm 2. This is why the propagation of waves around this frequency in arm 2 is precluded by the resonance of the 190nm long CWs. This insures that the light is well confined under the arm 1. In contrast, at the operating frequency of 188THz ($1.6\mu\text{m}$ wavelength), the effective index of hybrid waveguide with 140 and 190 nm long CWs is 2.87 and 3.08, respectively. The light is then redirected into the arm 2.

The validity of the effective medium approach results was further verified by the full 3D optical simulations of the device. To this end we performed full 3D HFSS [28] simulations with usual parameters of SOI slab waveguide ($2\mu\text{m}$ thick buried SiO₂ underclad, 220nm thick Si core, 5nm thick SiO₂ overlaid corresponding to the native oxide). The parameters of Au, Si and SiO₂ used in HFSS numerical simulations were taken from Palik [29].

The calculated distributions of light intensity at different wavelengths propagating across the hybrid plasmonic-photonic DMUX are shown in Figs 2(a) and 2(b). A clear spatial separation effect is observed for $1.3\mu\text{m}$ (230THz) and $1.62\mu\text{m}$ (185THz) wavelength. HFSS numerical simulations show also that the light is correctly guided at each frequency along the corresponding CWs metaline.

Fig. 2. HFSS modeling results for $1.3/1.6\mu\text{m}$ hybrid plasmonic-photonic DMUX. Distribution of propagating light intensity at different wavelengths: (a) $f=185\text{THz}$ ($\lambda=1.62\mu\text{m}$); (b) $f=230\text{THz}$ ($\lambda=1.3\mu\text{m}$).

3. FABRICATION AND EXPERIMENTAL RESULTS

Figure 3 shows the scanning electron microscope (SEM) view of the experimentally fabricated on chip DMUX based on the discussed above design: the DMUX is located at the end of a 600nm wide single mode waveguide (SMW), and a 500nm SMW is created at the end of each optical arm to collect the transmitted optical signals. The experimental prototype was fabricated by using a technological process involving two levels of e-beam lithography. The first lithography is dedicated to the definition of metallic elements pattern, i.e. nano CWs and second mask level alignment marks. This step is performed by means of NB4 electron-beam lithography setup using PMMA positive resist to define

the nanostructures patterns on the surface of undoped SOI wafer from SOITEC with 220nm thick top Si layer and 2 μ m BOX. It is followed by resist development and a double step e-beam evaporation to deposit a 2nm film of chromium as an adhesion layer, then a 50nm film of gold. The second e-beam lithography is dedicated to Si waveguides pattern definition using ZEP 520A positive resist. The residual resist is used after development as a soft mask for Si etching. Particular attention should be paid to the high precision alignment between the nano CWs and the Si waveguides patterns. This is achieved by utilizing the metal alignment mark implemented during the metallization step.

Fig. 3. SEM image view of a fabricated DMUX.

The optical setup employed for the characterization of fabricated wavelengthDMUX is illustrated in Fig. 4. Three tunable diode lasers of the T100S series from Yenista Optics used as a light source cover a spectral range from 1.25 μ m to 1.68 μ m. The linearly polarized light is coupled into a polarization maintaining lensed fiber that serves for light injection into the waveguide. The light propagating through the DMUX is collected from the silicon chip output side facet by a 32 $\times$ objective with 0.6 numerical aperture and then measured with a high sensitivity 1D CCD array IR camera used for registering the wavelength dependent spatial distribution of the transmitted intensity.

Fig. 4. Schematic of the end-fire optical bench setup.

The distribution of light intensity in output waveguides as a function of wavelength is shown in Fig. 5(a). The obtained experimental results bring clear evidence of efficient wavelength separation performed by the DMUX. For wavelengths comprised between 1.25 μ m and 1.4 μ m the light propagates in the arm 1 with a very weak level of light intensity in the arm 2. In contrast, for the wavelengths between 1.6 μ m and 1.68 μ m, the light propagates mainly in the arm 2, while the residual light intensity in the arm 1 is very low. To illustrate the efficiency of the DMUX wavelength separation Fig. 5(b) shows superposition of snapshots of IR CCD obtained at 1.355 μ m and 1.655 μ m wavelength. The extinction ratio between the channels is very high reaching up to two orders of magnitude (20dB).

Fig. 5. Experimental results: (a) Colormap of light intensity distribution as a function of wavelength for a hybrid plasmonic-photonic DMUX; (b) Distribution of light intensity in the output arms at 1355nm and 1655nm wavelength.

4. SUMMARY AND CONCLUSION

In conclusion, the demonstration of the wavelength separation produced by hybrid plasmonic-photonic DMUX unambiguously proves the ability for implementation of on demand light roads. In contrast to photonic crystals, the resonant nature of plasmonic nanoresonators inclusions allows a much higher degree of freedom for the wavelength dependent nanoscale engineering of the local effective index of the hybrid waveguide. Through an appropriate design of the resonant element, an effective index either higher or lower as that of the host slab waveguide can be obtained for a given wavelength. The extent of the effective index variation is essentially limited by the quality factor of gold plasmonic nanoresonator, which is relatively low in the NIR domain. By consequence, further improvement of the performances, that could be translated in a higher wavelength density of DMUX channels and even more smaller footprint, can be achieved by either considering applications in the MIR and THz domain, where metal related losses are negligible, or by extending the considered approach to all-dielectric metasurfaces and metalines [30].

The reported enabling technology is quite generic and can be readily adapted to different types of planar lightwave circuits platforms: Silicon, GaN/AlN, InGaAsP/InP, doped silica glass etc. It paves the way for a new class of wavelength sensitive guided wave optical metadevices suited for color routing applications.

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