Performance of electro-optical plasmonic ring resonators at telecom wavelengths

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Abstract: In this work we report on the characteristics of an electro-optical dielectric-loaded surface plasmon polariton waveguide ring resonator. By doping the dielectric host matrix with an electro-optical material and designing an appropriate set of planar electrodes, we measured a 16% relative change of transmission upon application of a controlled electric field. We have analyzed the temporal response of the device and conclude that electrostriction of the host matrix is playing a dominating role in the transmission response.

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References and links
1. Introduction

Plasmonics, a technology enabling a control over surface plasmon polaritons (SPP), is emerging because it provides a valuable platform to achieve compactness and high level of integration of photonic devices compatible with current electronic architectures [1, 2]. The control of surface plasmon field is usually obtained by structuring the metal surface supporting the SPP. Passive elements such as waveguides [3–5], routers [6–9], multiplexers [10] and more advanced devices [11] were successfully integrated in planar all-metal configurations. More recently, demonstrations of active plasmonic functionalities were reported in prototype devices fabricated on a wide range of supports including optical and electrical SPP modulations [12–14], ultrafast responses [15], transistor-like elements [16], and plasmon-based lasers [17]. These demonstrators, however, are currently not compatible with existing CMOS industrial standard and an alternative technology is therefore required to integrate active devices. Recently, a series of publications showed the potential of dielectric-loaded SPP waveguides (DLSPPW) to implement a plasmonic circuitry integrated on a Si architecture [18, 19]. Passive manipulation [20, 21], loss compensation [22], power monitoring [23] and thermal control [24] are already part of DLSPPW subunits. A DLSPPW configuration which shows high sensitivity to the change in refractive index of the dielectric load is the waveguide ring resonator (WRR) or disk resonator (WDR) geometry. For ring radius of $R = 5.5 \, \mu m$, the transmission can be modulated by about 10% when the refractive index of the load is changed by $\Delta n = 10^{-3}$ [25].

In this paper we analyze the possibility to achieve a hybrid plasmonic device operating at telecom wavelength by combining an active electro-optic polymer and a modified waveguide ring resonator (WRR) geometry with integrated in-plane electrodes. The electro-optical activity is created by doping the polymer load with Disperse-Red 1 (DR1) molecules, a chromophore known for its large electro-optic coefficient $r_{33}$ [26]. We fabricated devices using a two-step lithography procedure with precise alignment. By characterizing the performance of the devices with leakage radiation microscopy [27], we measure a relative change of the transmission of the device upon application of an external trigger voltage. Further details with respect to the modulation, its timescale and origins are discussed.

2. Device fabrication

The fabrication of the DLSPPW ring resonators was realized via a multi-step fabrication scheme as shown in Fig. 1(a). First, a set of electrodes was patterned by exposing with a 30 keV electron beam a 200 nm-thick Poly(methyl–methacrylate) (PMMA) layer on top of a 60 nm-thick Au film. After development, the exposed gold regions were etched using reactive ion etching with an argon plasma to form electrodes defined by isolated trenches having a gap of $g=4 \, \mu m$. A snapshot of the electrode layout design file is displayed in Fig.1(b). The fabricated electrodes were electrically tested in order to evaluate both their damage and short cut thresholds. Up to 55 MV/m have been successfully applied on the electrode without obtaining structural damages.

The second fabrication step concerns the preparation of the active dielectric load for the plasmonic waveguide. The load is an electro-optical (EO) polymer composite synthesized by doping a PMMA resist with DR1 molecules. The composite films showed refractive index change $\sim 10^{-4}$, which was measured experimentally by using attenuated total internal reflection technique [40]. The preparation of DR1/PMMA polymer layers was done by the following method: A powder of DR1 molecules (Sigma-Aldrich) were dissolved in chlorobenzene, stirred for 24 hours and filtered in order to obtain a more homogenous yet diluted solution. Then depending on the desired weight percentage, a given amount of DR1 was mixed with a solution of PMMA and chlorobenzene and kept stirring for about 2 hours. We found a weight percentage of 25% (calculated based on respective solution densities before filtering) for DR1-PMMA to be opti-
Fig. 1. (a) Overview of the various fabrication steps. (b) A snapshot of the design file depicts the electrode layout. The gray areas represent the isolating trenches between the electrodes. The crosses are the alignment marks used for precise fabrication of the WRRs on top of the electrode design.

Mal in terms of maximizing the electro-optical activity yet avoiding high absorption losses. In order to obtain films of PMMA/DR1, the solution was spin coated onto the substrate containing the electrodes at thickness around 500 nm, followed by drying of the films at 65°C in an oven to evaporate the solvent. For comparison purposes, undoped PMMA films were also deposited on pristine unstructured Au films and on substrates with electrode patterns.

Poling of the EO polymer was performed via the in-plane electrodes. The main advantage of using the in-built electrodes for poling is that there is no need for additional electrodes and their subsequent removal after poling. Samples were poled by applying a static electric field of 55 MV/m for about 30 minutes at 105°C and then cooled down to room temperature under applied electric poling field in order to freeze the oriented state of DR1 molecules.

From the spin-coated and poled DR1/PMMA composite, plasmonic waveguide ring and disk resonators (WRRs and WDRs) were patterned by a second step of electron beam lithography. Cross-like structures were used as alignment marks (see Fig. 1(b)) for accurate repositioning of the WRR structures between subsequent fabrication steps. For the fabrication of narrow coupling gaps between the ring and the waveguide it was important to consider proximity effect, which causes significant size variation due to the overexposure of regions adjacent to those exposed by electron beam. Proximity effect correction was used for patterning both the electrodes and later the waveguide ring resonators. A schematic of the complete device and a bright field image of the fabricated WRRs and WDR atop the gold electrodes are displayed in Fig. 2(a) and (b) respectively. In our configuration, the edge of the waveguide is designed to be at 700 nm away from the metal edge to avoid unnecessary damping of the plasmon mode at the edges [28, 29]. Following the same argumentation, the metallic bottom of ring resonator extends beyond the ring diameter $R$ by a value $w_s$ of 700 nm. However, due to inevitable drift during re-alignment of the multi-step fabrication, some WRRs are slightly off-centered as in
Fig. 2(b). The tapered structure at the entrance of the DLSPPW and the single slit located in the middle part of the funnel insure efficient SPP coupling in the DLSPPW [30, 41]. Similarly, towards the output section of the waveguide a periodic grating was placed to out-couple the transmitted DLSPPW mode.

Fig. 2. (a) A schematic showing the design of the WRRs placed on top of in-plane electrodes. (b) Bright field image of fabricated ring and disk resonators on top of Au electrodes. The dark area correspond to the isolating glass trench separating the two electrodes.

3. Device characterization

Leakage radiation microscopy (LRM) is a convenient and versatile far field optical method for analyzing quantitatively SPP propagation on flat films and in structured surfaces [31, 32]. LRM is a diffraction-limited technique based on the leaky nature of SPPs existing on a thin metal film and is advantageous in terms of rapid two dimensional mapping of SPPs when compared to scanning near-field microscopy [33]. Furthermore, direct and reciprocal space (Fourier plane) are accessible [9, 27] as well as observation with multiple wavelengths [34] and wavevectors [10]. However, LRM is restricted to leaky SPPs and limited to effective indices smaller than the numerical aperture of the collection objective.

In our configuration, we used a diascopic illumination to couple a tunable infrared laser source emitting around $\lambda = 1500$ nm in the telecom band. A long working distance objective with a numerical aperture of 0.52 focuses the collimated laser beam on a $\sim 2 \mu m$ diameter spot. The lateral position of the objective and the focused spot is adjusted to overlap the taper geometry at the entrance of the waveguide. We typically obtained a better coupling efficiency when the spot is diffracted by the slit opened in the taper. The polarization of the incident light is controlled by a combination of a polarizer and a half-wave plate. The leakage radiation of the DLSPPW mode is collected by a high numerical aperture objective (1.49) and is sent to infrared sensitive camera for imaging purposes.

The stop-band characteristic of resonator structures made of undoped and doped PMMA on planar Au films were evaluated using LRM. Typical images of a doped resonator’s on and off resonances are shown in Fig. 3(a) and (b). At the resonant excitation wavelength, here $\lambda = 1519$ nm, the transmission of the device is minimum. The spectral response of the WRR is plotted in Fig. 3(c) where the transmission $T$ is defined by:

$$T = 10 \times \log \left( \frac{I_{out}}{I_{in}} \right).$$

The input and output intensities $I_{in}$ and $I_{out}$ were evaluated by averaging the detected signal along the waveguide over two $3 \mu m \times 500$ nm areas placed before and after the ring resonator, respectively. The extinction ratio of the device reaches upto 7 dB. This value is typical for WRR
with ring radius $R=5.480 \, \mu m$ and coupling gap $d=150 \, nm$ [20, 21]. The quality factor for this device was evaluated at $Q = \frac{\lambda_{res}}{\Delta \lambda} = 190$ where $\lambda_{res}$ is the resonant wavelength and $\Delta \lambda$ is the full-width at half-maximum of the resonance.

We then investigated the response of WRR doped with poled DR1 molecules combined with the electrode layout discussed above. A typical image on and off resonance of the device for a null bias is shown in Fig. 4(a) and (b), respectively. Clearly, the contrast in the image is dominated by strong scattering of the focused beam onto the electrodes and the DLSPPW mode is overwhelmed by this unavoidable background. Under these conditions we were not able to measure an exploitable transmission curve and a background noise correction had to be implemented.

Drezet et al. demonstrated efficient surface plasmon filtering by placing appropriate beam stops in a conjugated Fourier plane of the microscope [35]. Following this approach, we have implemented spatial filters to block the directly transmitted light from the excitation, improving
thereby the accuracy of the measurements to a level where a transmission curve can be reason-
ably obtained. We have also modified the detection scheme to address the temporal response of
the device. Since a camera has limited time resolution, we have used a confocal-type detection
using an optical fiber coupled to a photomultiplier. The position of the fiber core was adjusted
on a conjugated image plane magnified outside the microscope to detect the output region of
the WRR. From the known core diameter and the magnification of the conjugated plane, the
confocal detection area was estimated to cover a diameter of approximately 3 μm. The wave-
length dependance of \( I_{\text{out}} \) for a null bias is shown in Fig. 4(c). Despite a remaining noise due
to limited spatial filtering, two rejection bands are clearly visible on the curve at 1517 nm and
1554 nm with an extinction ratio around 2.

![Confocal detection setup](image)

Fig. 5. Evolution of WRR output signal at 1508 nm, 1510 nm and 1516 nm for an upward
voltage sweep.

We have monitored the evolution of \( I_{\text{out}} \) for three wavelengths (in the proximity of the first
rejection band indicated by colored stars in Fig. 4(c)) as a function of a static electric field
applied between the in-plane electrodes. Figure 5 shows the results. Strong relative variation
occurs as the electric field is increased upto 8 MV/m for the three wavelengths. The trend
for low electric field indicates a red-shift of the resonance with voltage. A sharp fall of the
output amplitude is observed after 8 MV/m where \( I_{\text{out}} \) oscillates around its value at null bias.
We hypothesize that the low response for large electric field can be due to a deformation in
the PMMA structure due to an electrostrictive effect. Electrostriction will inevitably lead to a
deforation of the waveguide geometry and a change of its spectral response.

To further investigate this possibility, we focused on the kinetics of WRR output signal \( I_{\text{out}} \).
The \( I_{\text{out}} \) temporal response is correlated with the microscopic mechanisms responsible for the
observed variation. Kinetics were measured by monitoring the change in the time response of
the sample to a 0-100V square signal voltage (0-25MV/m), modulated at low frequency (50
mHz). The typical time response of the WRR output at its highest voltage sensitivity (green
curve in Fig. 5) is displayed in Fig. 6. Note due to a different alignment of the experimental
setup between measurements, the WRR output amplitude in Fig. 6 cannot be compared to
Fig. 5. The rise time of \( I_{\text{out}} \) following the step voltage is in the range of 1.3 s and was measured
consistently over a series of devices. Fall times are typically shorter by 20-30%. This slow time
response is clearly not in favor of an electro-optical effect where photonic devices containing
the same DR1 molecules were reported operating at kHz range [36, 37]. At this timescale the
signal variation has to be attributed most likely to either thermal changes due to electrical
leakage current or electrostriction effects. The measured residual current flowing between the
-electrodes was not exceeding 1 nA for the largest voltage applied (100 V). At this low current
value, thermal effect can be neglected [24, 38]. Electrostriction due to the volume contraction
of the polymer when a DC voltage is applied, has been observed before [39]. Therefore, we believe that the electrostrictive effects in PMMA play a dominating role in the variation of the WRR transmission.

Fig. 6. (a) PMMA-DR1 WRR output response time for an electric field step of 25 MV/m. (b) Controlled experiment with an undoped PMMA WRR.

To confirm this, we have fabricated undoped PMMA waveguide ring resonator on a planar electrode layout and measured the response dynamic as shown in Fig. 6(b). To fully recover the response time, the voltage modulation was decreased to 5 mHz. While the variation depth is approximatively equal in doped and undoped WRR (15%), rise and fall times are ten times slower in undoped WRR. This indicates that the presence of DR1 molecules seems to accelerate the electrostrictive process given that the PMMA thickness for both cases is similar. The reason for this behavior could be due to the modified plasticity of the doped PMMA compared to the pure one. Also, because the kinetics is dominated by the slowest time response, we cannot completely rule out the existence of an electro-optical effect at a much faster time scale. The response time of the doped WRR can be a mixed contribution of electrostrictive and electro-optical effects. We have systematically measured an hysteresis independent of the electric field polarity, most likely due to a fatigue caused by voltage stress. This kind of behavior tends to support our claim that the properties of electro-active DR1-PMMA plasmonic resonator can be dominated by electrostriction effects responsible for a relative variation of the WRR output transmission.

4. Conclusions

To summarize, we have fabricated and characterized active dielectric-loaded surface plasmon waveguide ring resonators. The dielectric load consists of a PMMA host matrix doped with Disperse-Red 1 molecules functioning as an electro-optical material. By applying an electric field between the electrodes, the transmission of the WRR was in excess of 10%. By investigating the kinetics of the transmission when a stress voltage is applied, we found a response time in the order of a second. We have attributed this slow kinetics to a dominating electrostrictive effect directly affecting the geometry of the structure. We believe that these type of counter effects should not be ignored and considered seriously in the future design of electro-active plasmonic devices using similar configurations.

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