Bypassing Loss in Plasmonic Modulators

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Abstract: We show that Ohmic losses in plasmonic modulators can be bypassed by using a resonant scheme. This enables the first modulator that unites low-loss, high-speed, compact footprint and low-electrical energy consumption.

OCIS codes: (250.5403) Plasmonics; (250.4110) Modulators, (230.5750) Resonators

1. Introduction

Plasmonic-based electro-optic modulators feature the unique property of confining light below the diffraction limit, which enhances the light-matter interaction (LMI) and enables μm-long devices [1]. This is especially true for metal-insulator-metal waveguides, where the metals additionally serve as high-speed contact electrodes. However, the Ohmic loss inherent to metals poses a fundamental challenge to the realization of a modulator that combines high-speed and a compact footprint with low power switching and low insertion loss (IL).

To reduce IL, hybrid plasmonic waveguides have been introduced which optimize modulator performance by trading confinement and speed with Ohmic loss [2, 3]. An alternative strategy is to reduce the interaction length by utilizing highly nonlinear $\chi^{(2)}$ materials. However, these demonstrations have not yet succeeded in reducing insertion loss below 8 dB [4, 5]. Alternatively, we can leverage knowledge from photonics, which employs ring and disc resonators to enable a reduction in size from millimeter-long phase shifters to μm-scales, while featuring similar sensitivities [6, 7]. More importantly, in the through-state only a fraction of the light couples to the doped and therefore "lossy" resonator.

Here, we show that the bypassing mechanism of a resonant approach enables a significant reduction of IL while the plasmonic-enhanced LMI allows overcoming the trade-off between high speed and low driving voltages of photonic resonators. This is verified by our most recent experimental results, showing the first modulator that unites low IL (2.5 dB), broad electro-optic bandwidth (>100GHz), low energy switching (~10fJ/Bit at 72Gbit/s) and a compact footprint of 7μm^2, [8].

2. Bypassing Ohmic loss

Fig. 1 shows an SEM image of the proposed plasmonic ring resonator coupled to a silicon bus waveguide. The resonator consists of a circular plasmonic slot waveguide, which is filled with an organic electro-optic material [9]. Light traveling in the bus waveguide partially couples (κ) to surface plasmon polaritons (SPPs) propagating in the resonator and is partially transmitted (τ) with an overall coupling efficiency of $C = \tau^2 + \kappa^2 < 1$, which is limited by Ohmic loss [10].

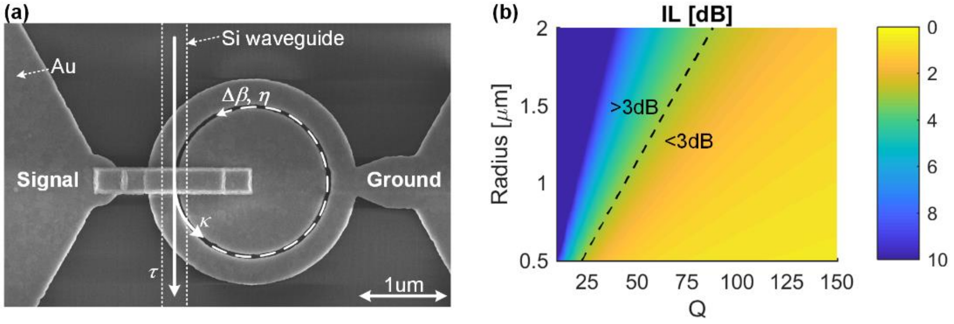

Fig. 1: (a) SEM images of the fabricated ring resonator. The Si waveguide is buried underneath the Au resonator, whereas the vertical spacing enables a well controllable adjustment of the coupling coefficients (κ, τ). (b) Calculated IL as a function of the intrinsic Q-factor and radius.

Upon fulfilling the resonance condition (off-state), all light is coupled into the resonator and the transmitted intensity approaches zero. By applying a voltage to the signal and contact pad, the resonance condition is changed by the Pockels effect ($\Delta\beta$). In the modulator "on"-state, only a fraction $1/\kappa^2$ of the incident photons experiences Ohmic loss, while the rest passes without significant loos of power. The required κ is defined by the critical coupling condition and increases with decreasing Q-factors. Fig. 1 shows, the calculated IL at 1.55µm over the radius and the cavity's intrinsic quality factor. Loss below 3 dB are already feasible for low Q-factors of 50 and a sub-wavelength radius, while loss of 1 dB are achievable for a moderate Q of 100.

3. Q-factors in plasmonic MIM ring resonators

In ring resonators, bending loss and propagation loss defines the Q-factor, and thus, Q is a function of geometrical parameters such as radius (R) and slot width (w), see Fig. 2(a). The Q-factor for the three different slot widths saturate for large radii when Ohmic loss dominates, whereas it falls off with decreasing radius (bending loss). The bending loss starts to dominate at smaller radii for smaller slot width due to the tighter SPP confinement. However, this confinement comes at the cost of higher Ohmic loss that limits the achievable Q-factors at large radii. A device with a 1 µm radius and a 75 nm wide slot offers a good trade-off between strong LMI ($\propto Q/w$) and small IL ($\propto R/Q$), see Fig. 2(b). For such a device IL down to 2 dB are possible, while a resonance wavelength shift of several nm/V provides an efficient modulation mechanism. Furthermore, we expect a THz electro-optic bandwidth due to the moderate Q-factors. Fig. 2(c) shows the eye diagram of an 72Gbit/s electrical signal encoded by the ring resonator as discussed in ref. [8].

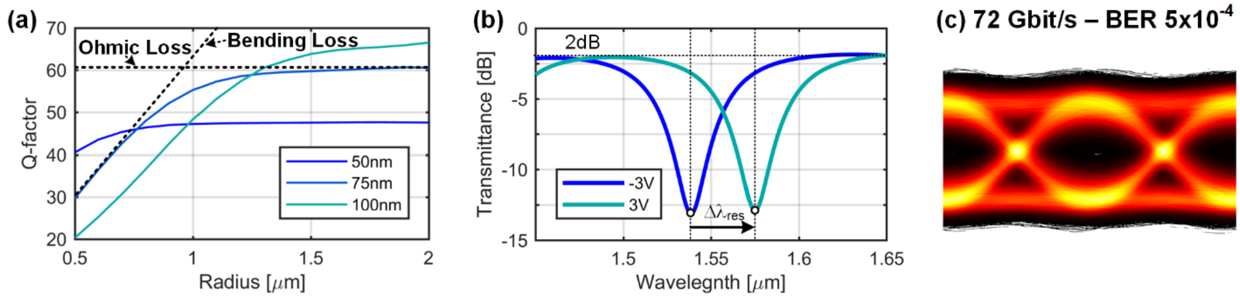

Fig. 2: (a) Q-factor over the bending radius of a gold plasmonic slot waveguide for various slot widths. (b) Transfer function over wavelength for different biasing conditions, an electro-optic coefficient of r33=200pm/V and a ring radius and slot width of 1 µm and 75 nm, respectively. (c) Measured eye diagram of a plasmonic ring resonator at 72 Gbit/s.

4. Conclusion

Our results show that plasmonic resonators are a viable solution to bypass loss in plasmonic modulators. This enables compact, low-loss, high-speed and energy-efficient electro-optic modulators as it is unknown from prior technology. These findings are supported by our recent experimental results as will be discussed in this talk [8].

Acknowledgments

This work was partly carried out at the BRNC and FIRST of ETH Zurich. The EU-project PLASMOfab (688166), ERC PLASILOR (670478), NSF (DMR-1303080) and AFOSR (FA9550-15-1-0319 and FA9550-14-1-0138) are acknowledged for financial support. N. K. acknowledges support from the Virginia Microelectronics Consortium and the Virginia Commonwealth University Presidential Research Quest Fund.

4. References

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