Modulation Enhancement Through Resonant Microwave-Photonic Co-Design

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Abstract Above 3 dB modulation enhancement is demonstrated by cointegrating a resonant microwave circuit with a lumped-element plasmonic modulator. The resonant circuit can compensate electronic driver roll-offs and enable increased transmitter bandwidths. Furthermore, the circuit is complemented by an integrated bias-Tee to tune the modulator. ©2023 The Authors

Introduction

Optical modulators ought to operate with the least possible voltage and should feature a broadband frequency response on a compact footprint.

To reduce the operation voltage, pre-emphasis techniques on the drive signals may be employed, one of which is inductive peaking [1-3]. Inductive peaking reduces the required voltage using two distinct effects: (A) Through impedance matching that optimises the power delivered to the load. Impedance matching may be employed on any device configuration, e.g. travelling-wave Mach-Zehnder modulators [1] or lumped-element modulators [2, 3]. (B) Through resonant enhancement where the modulator is part of a resonant microwave circuit. This resonant enhancement may only be employed for lumped-element modulators as in [2, 3]. Yet, inductive peaking is governed by a gain-bandwidth trade-off and higher gain usually comes at a price of a bandwidth reduction. Therefore, a high-bandwidth photonic technology is advantageous to fully exploit inductive peaking.

State-of-the-art plasmonic modulators offer broad bandwidth [4] and low drive voltages [5] on a compact footprint [6]. They can be cointegrated with electronic circuits [7, 8] and recent devices demonstrate low insertion losses [9]. These modulators can be modelled as tiny capacitors that may be embedded within a resonant circuit. Since they are broadband and offer >500 GHz bandwidth [4], they are well suited for inductive peaking. The large excess bandwidth gives an enormous margin to be traded in for gain.

In this work, modulation enhancement through inductive peaking is demonstrated for a plasmonic modulator, cf. Fig. 1. The use of an LC-resonator provides voltage gain in exchange for excess bandwidth. Simulations predict a >3 dB enhancement at 70 GHz and a >10 dB enhancement at 100 GHz. The experiment confirms the >3 dB enhancement at 70 GHz. Furthermore, the frequency behaviour of the resonant circuit was used to compensate for the roll-off of the electronic driver circuit, i.e., to flatten the overall response. The broadband pre-emphasis filter



Fig. 1: (a) Depiction of a reference plasmonic modulator. (b) Structure of an inductive peaking modulator offering a built-in gain enhancement between 40 GHz and 100 GHz. The circuit comprises of a plasmonic modulator as part of an LC-resonator. A bias-T is co-designed with the circuit to offset-bias the modulator.

improves the signal quality over a wide range from 40 GHz to 100 GHz. In addition to inductive peaking, a broadband bias-Tee was implemented in the same layer to tune the modulator.

The Electro-Optic Modulators

To test the concept, a plasmonic reference modulator was fabricated, Fig. 1(a), and used as comparison with an adjacently placed inductively peaking plasmonic modulator, Fig. 1(b).

The reference modulator has no additional microwave circuitry, while the peaking plasmonic modulator is enhanced by means of a resonant LC-circuit. The plasmonic modulator thereby acts as a lumped element capacitor. A bias-Tee was added to the circuit allowing offset-biasing of the modulator (which will be useful if the phase modulator will be a part of a Mach-Zehnder modulator). Both plasmonic modulators were fabricated, activated and characterised simultaneously to preclude the influence of external factors on the measurement.

The plasmonic phase shifters and the microwave components were fabricated in a gold layer using a standard electron-beam-lithographybased process. The photonic waveguides consist of a 220 nm high silicon ridge on silicon dioxide. The active electro-optical material BAHX was spin-coated and poled electrostatically. It is a cross-linkable variant of the high-performance BAH13 material [10, 11].

The Resonant Circuit

The circuit is composed of an LC-resonator coupled to a bias-Tee. The simplified schematic is depicted in Fig 2. The plasmonic modulator is modelled as a pure capacitor. The optimal parameters were found by a lumped-elements simulation (LTSpice). The unknown model parameters were inferred from prior measurements of fabricated structures. The simulation predicts a





Fig. 2: Lumped-element circuit model of the device presented in Fig. 1. The plasmonic modulator can be modelled by a single 5 fF capacitor. The resonant enhancement is induced by a ~250 pH resonant inductor, coupled to a 5 fF resonant capacitor. The bias-Tee is formed by a ~50 μH inductor and a 70 fF capacitor. The component values above are approximate and extracted/extrapolated from measurements of reference structures.

resonant enhancement of >10 dB at 100 GHz and a 3 dB modulation bandwidth of >100 GHz.

Relevant for modulation is the voltage across the modulator. Due to reflection at the lumped capacitance of the plasmonic modulator, this voltage is conventionally two times the injected voltage since the frequencies are well below the RC limit. Without breaking energy conservation, this factor can be increased by resonant enhancement. The only limit is the gain-bandwidth-product, i.e., the enhancement comes at the price of reduced bandwidth. Assuming that a plasmonic modulator has 1 THz bandwidth, the resonant circuit can be designed for a peaking of ~10 dB, while still offering gain in a window of ~100 GHz bandwidth. In this configuration, it will not impair currently available transmission systems.



(a) Electro-Optical Measurement

(b) Measured Enhancement

Fig. 3: Measured and simulated frequency responses of the inductive peaking modulator. (a) Normalised peak-to-sideband ratio (PSPR) of a peaking modulator (blue) and a reference modulator (red). It can be seen that the peaking circuit can compensate the electrical loss and flatten the frequency response. (b) Comparison of the frequency-dependent enhancement of the measured against simulated frequency response. In measurement, a relative enhancement of >3 dB is demonstrated at 70 GHz. Simulations show that even larger enhancement is possible towards 100 GHz.



Fig. 4: In a digital data transmission experiment, the measured transfer functions were applied to 120 Gb/s signals. The eye diagram of (a) the reference modulator is compared to (b) the enhanced peaking modulator. (c) The resonant enhancement translates into the power spectral density (PSD) of the transmitted signals. The PSD of the back-to-back (B2B) signal is compared with the ones shaped with the transfer functions derived from the reference and peaking device.

Measurements

Experimentally, we found a resonant enhancement of 3.5 dB within a spectral range from 7 GHz to 70 GHz, see Fig. 3. The gain around 100 GHz might actually be larger. Yet, characterization at 100 GHz requires an extra setup, which was not available at the time of the experiment.

The frequency response of the reference and peaking modulators in Fig. 3(a) were obtained by applying a sinusoidal 10 dBm microwave signal with oscillation frequencies between 7 GHz and 70 GHz and measuring the electro-optical response. The microwave source was coupled to the device using a 1 m long RF cable and a single GSG microwave probe. The electronic frequency response of the set-up drops from a collective 1.7 dB loss at 7 GHz to 5.1 dB at 70 GHz. Optically, laser light at 1560 nm was coupled through conventional grating couplers and the modulation sidebands were observed in an optical spectrum analyser. The carrier transmission was measured to be identical (<0.2 dB variation), confirming that the modulators have the same optical properties.

Inductive peaking provided a modulation enhancement by 3.5 dB at 70 GHz. On top, the frequency response roll-off is reduced by 2.8 dB. The enhancement is in agreement with the simulated response, see Fig. 3(b).

Impact on Data Transmission

To understand the impact on data transmission, the frequency response of a modulator in a 120 GBd data transmission simulation was replaced by the measured one.

The resulting signals are plotted in Fig. 4. The additional gain at high frequencies directly translates into a higher signal-to-noise ratio (SNR) and a lower bit-error ratio (BER), see Fig. 4(a, b). Fig. 4(c) shows the power spectral density of the electrical signal fed to the modulator (yellow). The

red and blue spectra show the received electrical signals as transmitted by the reference and the peaking modulators, respectively.

Conclusions

The concept of inductive peaking was applied to plasmonics to enhance the modulation efficiency. While simulations predict a 10 dB peaking towards 100 GHz, >3 dB modulation improvement was found in experiment within the first 70 GHz. Inductive peaking was used to compensate the roll-off of the electronic equipment by the resonant behaviour of the peaking LC-circuit.

A bias-Tee was fabricated within the same plasmonic layer, leveraging the high-resolution lithography of plasmonics to cointegrate electronics. Here, a bias-Tee with 70 fF capacitor was implemented on a compact 450 μ m² footprint.

A simple but efficient, lumped-element technique to model the impact of the circuits is provided together with extracted component values.

This work shows how co-designing microwave circuits with electro-optic modulators in the same layer can greatly benefit the modulator's performance. Inductive peaking can flatten the frequency response of an electronic circuit and extend the combined 3 dB-bandwidth of electrooptic transmitters.

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