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Plasmonic Modulators for Microwave Photonics Applications

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Abstract: We discuss the potential of ultrafast (>170 GHz) and ultra-compact (10s µm^2) plasmonic modulators on silicon for microwave photonics applications, with emphasis on mm-wave and sub-THz wireless communications and signal processing.

OCIS codes: (250.5403) Plasmonics; (250.4390) Nonlinear optics, integrated optics; (060.5625) Radio frequency photonics.

1. Introduction

Integrated microwave photonics (IMWP) is a discipline that deals with the use of photonic integrated circuits for the implementation of microwave, mm-wave and sub-THz signal generation, transport and processing functions [1]. IMWP techniques aim to surpass the performance of all-electronic systems by leveraging the frequency flexibility and broad bandwidth of operation of photonics. As such, they have been identified as enabling technologies for next generation (5G) wireless communication systems, for example to provide optical signal generation and distribution of mm-waves towards antenna terminals [2], frequency-reconfigurable filtering [3], optical control of antenna arrays [2, 4], and more [5]. 5G applications, however, pose very stringent requirements on the speed of IMWP circuits, which may need the ability to process mm-wave or even sub-THz frequencies, to access the multi-GHz bandwidths required for high data rates [6, 7]. Comparably fast modulators (operating up to sub-THz speeds) with small power and footprint, fabricated using a low-cost, CMOS compatible process are not yet broadly available. Plasmonic modulators recently demonstrated ultra-fast operation (>170 GHz), with ultra-compact footprints (10s µm^2) and ultra-low power consumption (10s fJ/bit) [8-16]. Here we discuss the application of this novel platform to IMWP systems [5, 17].

2. Principle of operation of plasmonic modulators

Plasmonic phase modulators (PPMs) [12] are based on surface plasmon polaritons (SPP), which are electromagnetic surface waves propagating at a dielectric-metal interface. A PPM, Fig. 1(a), can be realized creating a metal-insulator-metal (MIM) slot between two gold electrodes, and filling it with a nonlinear χ^2 material [18, 19]. The modulation is based on the fact that the refractive index of the nonlinear material in the slot varies linearly with the electric field across the slot, according to Pockels effect [20]. The electric field is created by applying a potential difference between the electrodes. Light may be fed to the plasmonic slot by a variety of means, a simple solution being the use of a silicon strip waveguide terminated on a tapered photonic-plasmonic converter. This taper transforms the input photonic mode to a SPP that propagates along the slot. The phase of the propagating SPP is modulated by the applied electrical field, as described above, before being coupled back to an output photonic mode. This architecture allows high modulation indexes, thanks to the strong electrical and optical field confinement in the slot and the very good overlap between the optical and electrical field modes, see Fig. 1(b, c). In turn, the high modulation index allows to keep the plasmonic slot very short and thus to limit the optical loss. A particularly attractive characteristic of those modulators for IMWP is the very high RF bandwidth, due to the quasi-instantaneous nature of Pockels effect and the extremely small RC time constant of the structure, thanks to the high conductivity of the electrodes and the low capacitance (in the femtofarad range) of the slot. Compactness is another crucial advantage of these modulators that, compared to traditional broadband modulators based on a travelling

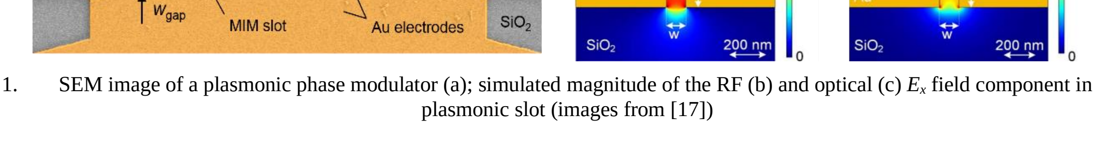

Fig. 1. SEM image of a plasmonic phase modulator (a); simulated magnitude of the RF (b) and optical (c) E_x field component in the plasmonic slot (images from [17])

wave structure, overcome the size mismatch with integrated electronics and may open the path to efficient electronics-photonics co-integration [21]. Plasmonic phase modulators have been arranged in a number of configurations to create intensity modulators [14, 16] and IQ modulators [13]. Intensity modulators reaching 170 GHz speeds, limited only by the experimental setup, have recently been demonstrated [15], enabling new optical interconnect solutions [22] and mm-wave and sub-THz signal processing schemes for future wireless communications and sensing applications. Recent works revealed the crucial influence of the nanoscale metallic slot quality and width on the nonlinear material performance [23] and employed material resonances to further enhance the modulation efficiency [24].

3. Plasmonic modulators enabling radio frequency photonic systems

We now describe two practical examples of application of plasmonic modulators to microwave photonic systems. Salamin *et al.* reported a solution for direct conversion of free-space wireless radio signals to the optical domain, without resorting to complex high-frequency electronic receivers, by co-integrating a 60 GHz resonant antenna with a plasmonic modulator [25]. In [26], a PPM was integrated into a four-clover-leaf shaped antenna, where the antenna arms are directly connected to the plasmonic slot of the PPM, Fig. 2(a-c). The modulation efficiency is enhanced by designing the antenna arms to be resonant at the target RF frequency. The resulting electric field across the plasmonic slot is enhanced by a factor of 92’000 compared with the incident mm-wave field. Owing to the broadband characteristics of the modulator, this scheme can be extended to sub-THz frequencies by scaling the size of the antenna accordingly.

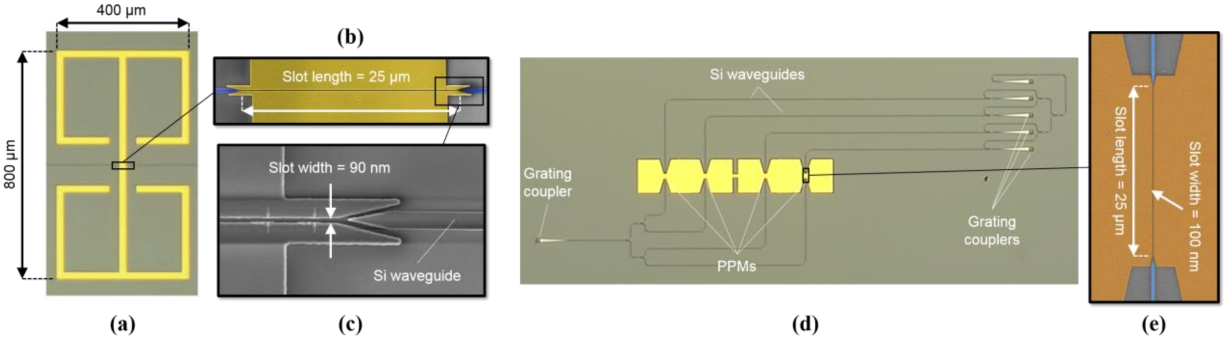

Fig. 2. Four-clover-leaf antenna (a): detail of the PPM (b) and of the plasmonic slot (c) [26]; plasmonic beamformer (d) based on PPMs (e) employed for 60 GHz beamsteering experiments [28].

In practical deployments of 5G wireless communications, directive antennas with capability to focus radiation towards individual users will likely be required in order to compensate for the larger free space path losses of mm-waves compared to microwave frequencies. In these schemes, beam steering techniques are considered to provide uninterrupted connectivity to moving users. Bonjour *et al.* [27] proposed a technique to increase the 5G cell capacity known as symbol-by-symbol beam steering. This technique consists in encoding the data aimed at different users in consecutive time slots. The antenna beam direction is then switched at the same speed as the symbol period, employing fast phase shifters before each antenna, such that consecutive transmitted bits are sent to different users. For high capacity multi-Gbit data links, the switching time may be as short as a few picoseconds, which requires very fast tunable phase shifters. We recently reported an antenna beamformer where the phase shifters are realized by an array of 4 PPMs, used to control the beam direction of a 4-element linear antenna array. Images of the beamforming chip and of one PPM are shown in Fig. 2(d-e), and details on the operating principle are reported in [28]. Preliminary results of data transmission experiments show successful symbol-by-symbol steering capability up to 1 GBaud transmitted QPSK signals.

The results discussed here show the promising capabilities of plasmonic modulators to improve the performance of microwave photonics systems, enabling speeds well above 100 GHz while providing high compactness. These are crucial characteristics for future IMWP systems, which are expected to provide high frequency operation while retaining low footprint and cost.

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