MEMS Plasmonics and Memristive Plasmonics for Optical Communications

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Abstract *Plasmonics allows for an unmatched miniaturization. Along with the shrinking comes power efficient operation. Here, we show how plasmonics allows for an unprecedented downscaling of the classical MEMS and even of emerging memristive approaches. Ultimately, we will demonstrate optical elements at the atomic scale.*

Introduction

Plasmonics holds promise for an unmatched miniaturization, operation of devices at highest speed and at low power consumption [1-6]. And indeed, research in plasmonics has a long history with an even longer list of unmatched promises [7-9]. Until recently one could at best find active plasmonic devices with MHz operation at unprecedented loss levels.

Yet, the situation has changed in the last few years. Ever since the first high-speed plasmonic phase modulator has emerged in 2014 [10], the field has progressed. Meanwhile, plasmonic MZI [11], IQ [12] and ring modulators [13] offering bandwidths in excess of 500 GHz [14], atto-Joule per bit operation at 100 Gbit/s [15] with μm^2 footprints [13, 16] and on-chip losses in the order of 2.5 [13] to 8 dB [13] for the respective devices have emerged. Likewise, there has been progress in the field of plasmonic photodetectors [17], where devices with bandwidths of 100 GHz [18] and responsivities of 0.55 A/W at 100 GHz have been published [19]. Similarly, the millimetre wave and THz field community is benefitting from new plasmonic antenna reception schemes [20, 21]. More recently, plasmonics has been applied to MEMS in an effort to downscale the traditionally large dimensions in said field [22, 23]. As a result it has been shown, that MEMS switches can operate with CMOS voltages of 1V and losses in the order of 0.1 and 2.0 dB for the through and drop ports, respectively [23].

In this paper we discuss in a first part the most recent developments in the field of MEMS plasmonics. We then discuss the ultimate limit of integrated optics and discuss recent developments in the field of single atom photonics – or more precisely on memristive plasmonics. Naturally, the focus will be on the most recent MEMS plasmonic publications [23] and single atom device publications [24, 25] of the authors.

MEMS Plasmonics

MEMS technology has become widely available in optical communications. However, footprint and operation voltages are rather large. Here, plasmonics offers a path towards a miniaturization [22, 23].. If a photon is converted to a surface plasmon polariton, its dimension shrinks to sub a diffraction limited size (typically 10s and 100s of nanometers.) Consequently, plasmonic modes can be confined to much more compact waveguides. In a compact plasmonic waveguide a tiny change on the dimension then leads to a large change in the effective group refractive index. This fact is then exploited in plasmonic MEMS where tiny mechanical changes have a large impact on the propagation constant of the mode. In addition, a small waveguide geometry d relaxes the required voltage for bending of a waveguide as the electric field E inversely scales with the applied voltage U by $E \sim U/d$, [23]. Lastly, smaller dimensions lead to higher mechanical resonance frequencies than what is known from traditional MEMS switches .

Recently, a nano-MEMS plasmonic switch controlled by CMOS-level voltages (≈1.4 V), operating with low optical losses of 0.1 dB in the through port and 2 dB in the drop port, a small footprint of ~10 μm^2 and switching times in the tens of nanoseconds has been published. A schematic of the switch is depicted in Fig. 1.The plot shows ring type switches that are arranged along a Manhatten type optical waveguide grid. The rings comprise of a metal top plate and a conductive bottom silicon layer followed and are fabricated on SiO_2 substrates. The silicon layer serves as guiding layer for a whispering gallery mode in the ring. The combination of top metal with an air gap slot followed by the silicon waveguide allows the formation of hybrid plasmonic modes. Due to the low refractive index in the air gap a good fraction of the mode will be concentrated in this gap. Switching is then performed in this gap. The ring type switches are placed in the vicinity of the Manhatten type waveguides to enable efficient coupling. A waveguide mode will couple to the plasmonic ring modes when the resonance conditions of the ring are met. I.e. when the effective refractive index of the hybrid modes are properly tuned.

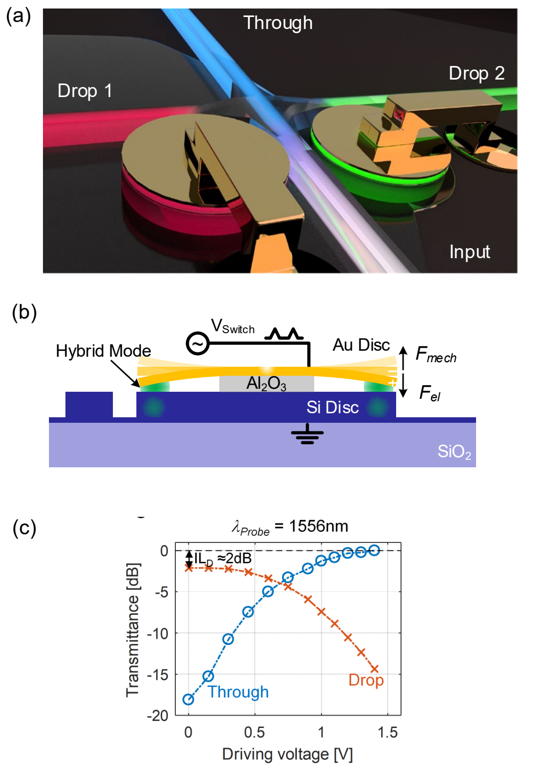

Fig. 1: Nano-MEMS plasmonic switch. (a) Brid view of two hybrid plasmonic rings that are coupled to silicon photonic waveguides. Depending on the state of the rings, an optical mode from the input will coupled to the through or the drop ports. (b) Side view of the ring resonator. A hybrid plasmonic mode propagates within the ring. The top metal will bend downwards if a voltage is applied between the top metal and the bottom silicon layer. As a consequence a hybrid plasmonic mode will couple to a drop port. (c) Transmission characteristic of through and drop port when applying a voltage, see [22].

The effective refractive index of the hybrid modes can be tuned by applying a voltage between the metallic top plate and the conductive silicon layer. If no voltage is applied, a waveguide mode will not couple to the hybrid mode and an input signal will be passed to the through port. If a voltage is applied, the top layer of the ring will bend. A small change on the distance between top metal and silicon layer will drastically increase the effective refractive index of the mode, see Fig. 1(b). A small voltage is sufficient to perform switching. The low power consumption requirements can be understood by the fact that the plasmonic air gap thickness d is small. Thus, a small voltage drop across the gap will be accompanied by a large electric field that will efficiently bend the top metal layer. Beyond, the electric field is enhanced due to the plasmonic ring resonance featuring a Q-factor in the order of 1000, see [13, 23]. Also, since surface plasmonic modes are small, a small change of the mode geometry comes along with large effective refractive index changes. All of which makes the switch very efficient and allows for switching voltages in the order of 1.4 V. In addition, the compact size with the small masses also allows for fast operation with MHz bandwidth. Lastly, it should be mentioned that the plasmonic MEMS switch features low loss operation. The through port allows bypassing of the ring with as little loss as 0.1 dB. When coupling to the ring and dropping the mode the excess chip losses are in the order of 2 dB.

Atomic Scale Plasmonics

Plasmonics is a path towards downscaling. In fact, plasmonics allows an unprecedented downscaling of functional devices to the atomic level [26, 27].

The idea of single atom plasmonic devices goes back to the memristive effect. In memristive devices conductive filament channels interconnect metallic pads [28, 29]. In the presence of a filament, the device become conductive. In fact, a single conductive atom that connects two pads is sufficient to dramatically increase the conductivity. In the absence, the devices are highly resistive. The conductive and resistive state then define two electrical states. The same electrical states in this geometry can also define that operation modes of two plasmonic states. This is best understood by discussing the single atom photodetector device depicted in Fig. 2(a), Ref. [25].

In Fig. 2(a) one can see a metallic Ag top pad. It tips downwards towards a metallic Pt bottom pad. The two are separated by a thin SiO_2 matrix. The two pads act as memristive pads as described above. The two pads might be connected by conductive or resistive filament depending, see Fig. 2(b). The plot in Fig. 2(a) also shows a silicon waveguide that is sandwiched between the two pads. The photodetector operation principle now is as follows. Upon irradiation of the waveguide with an optical signal, a plasmon is formed at the metallic pads. The plasmon leads to heat generation between the two pads due to plasmonic absorption. As a consequence a possible filament between the two pads dissolves, see Fig. 2(b) bottom plot. Only small optical powers are needed since the diffusion of a single silver atom suffices to disrupt the filament and to detect the influx of photons. In the absence of an optical signal the atom will resume its position and again bond and form a conductive filament, [25], see Fig. 2(b) top plot It should be noted, that the detector operates reliably, as can be seen by the clear and open eye diagrams in Ref. [25].

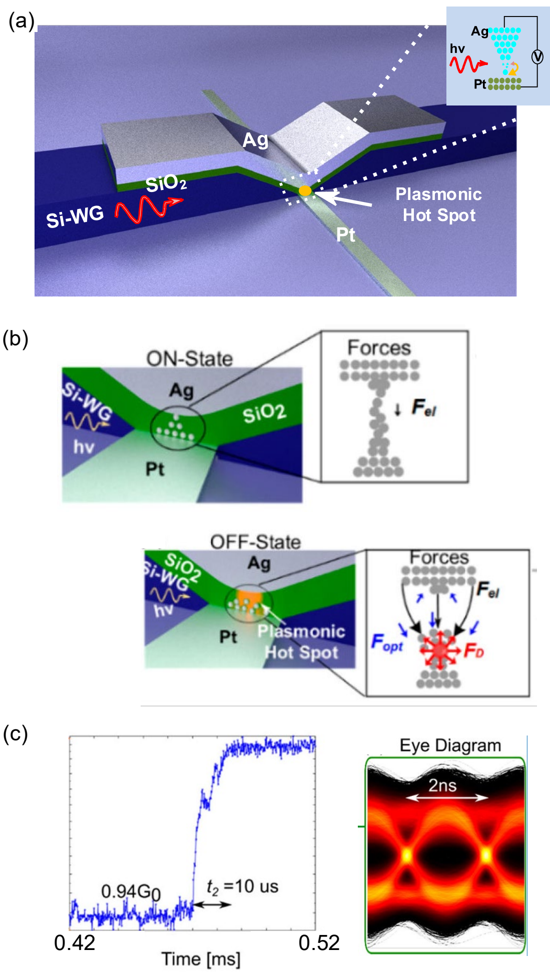

Fig. 2: Single atom photodetector. (a) Structure of the detector. A silicon waveguide that can support an incident optical signal is launched towards a metal-insulator-metal plasmonic section. The plasmonic section comprises of a silver-insulator-patinum section. (b) The operation principle is best understood with the help of the two plots. A filament interconnects the top and bottom electrocdes in the absence of a photon. Upon irradiation the head dissipated by the plasmons will dilute the filament and the circuited is interrupted. (c) Transients showing details of the dynamics. An eye diagram shows reliable detection of a signal [24].

Likewise a single atom plasmonic switch has been introduced [24]. In this switch a tiny filament within the plasmonic metal-insulator-slot is connected or interrupted by applying a small voltage. The required fields meanwhile are in the order of 100 of mV [30]. Reliable operation with bandwidths of a few 100 MHz has already been shown [24]. And while there is still a long path to make these switches as reliable and low loss as its plasmonic or photonic counterparts, these initial demonstrations show that there is a path beyond Moore - not just for electronics, but also for photonics.

Conclusions

Plasmonics is a path to downscale the large footprints of optical elements. Meanwhile, routes have been shown to replace active plasmonic devices for modulation, detection or switching. In the future, plasmonics will likely replace photonic elements when speed, power-consumption and footprint matter. And while plasmonic losses are still higher than what is known from its photonic counterparts, progress towards lower loss components is made. First high-speed plasmonic modulators and MEMS switches with on-chip losses of 2 dB have already been shown.

Acknowledgements

Funding by the Werner Siemens foundation (WSS) for the Center for Single-Atom Electronics and Photonics, as well as funding by the ERC PLASILOR (grant 670478) and the EU project plaCMOS (grant 980997) is acknowledged.

References

[1] T. Nikolajsen, K. Leosson, and S. I. Bozhevolnyi, "Surface plasmon polariton based modulators and switches operating at telecom wavelengths," *Applied Physics Letters,* vol. 85, no. 24, pp. 5833-5835, 2004.

[2] H. A. Atwater, "The Promise of Plasmonics," *Scientific American,* vol. 296, no. 4, p. 56.62, 2007.

[3] A. Polman, "Plasmonics Applied," *Science,* vol. 322, no. 5903, pp. 868-869, 2008.

[4] M. L. Brongersma and V. M. Shalaev, "The Case for Plasmonics," *Science,* vol. 328, no. 5977, pp. 440-441, April 2010.

[5] J. Leuthold *et al.* (2013, May) Plasmonic Communications - LIGHT ON A WIRE *Optics & Photonics News*. 28-35.

[6] L. Thylen and L. Wosinski, "Integrated photonics in the 21st century," *Photonics Research,* vol. 2, no. 2, pp. 75-81, 2014.

[7] I. P. Kaminow, W. L. Mammel, and H. P. Weber, "Metal-clad optical waveguides: Analytical and experimental study " *Appl. Opt.,* vol. 13, no. 2, p. 396, Feb. 1974.

[8] J. S. Schildkraut, "Long-range surface plasmon electrooptic modulator," *Appl. Opt.,* vol. 27, no. 21, pp. 4587-4590, Nov 1988.

[9] A. D. Rakić, A. B. Djurišić, J. M. Elazar, and M. L. Majewski, "Optical properties of metallic films for vertical-cavity optoelectronic devices," *Appl. Opt.,* vol. 37, no. 22, pp. 5271-5283, Aug. 1998.

[10] A. Melikyan *et al.*, "High-speed plasmonic phase modulators," *Nature Photonics,* Letter vol. 8, no. 3, pp. 229-233, March 2014.

[11] C. Haffner *et al.*, "All-plasmonic Mach–Zehnder modulator enabling optical high-speed communication at the microscale," *Nature Photonics,* Letter vol. 9, pp. 525-528, Aug. 2015.

[12] C. Haffner *et al.*, "Plasmonic Organic Hybrid Modulators – Scaling Highest-Speed Photonics to the Microscale," *Proceedings of the IEEE,* vol. 104, no. 12, pp. 2362 - 2379, Dec. 2016.

[13] C. Haffner *et al.*, "Low-loss plasmon-assisted electro-optic modulator," *Nature,* vol. 556, no. 7702, pp. 483-486, April 2018.

[14] M. Burla *et al.*, "500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics," *APL Photonics,* vol. 4, no. 5, p. 056106, May 2019.

[15] W. Heni *et al.*, "Plasmonic IQ modulators with attojoule per bit electrical energy consumption," *Nature Communications,* vol. 10, no. 1, p. 1694, April 2019.

[16] M. Ayata *et al.*, "High-speed plasmonic modulator in a single metal layer," *Science,* vol. 358, no. 6363, pp. 630-632, Nov. 2017.

[17] A. Dorodnyy *et al.*, "Plasmonic Photodetectors," *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 24, no. 6, p. 4600313, Nov./Dec. 2018.

[18] Y. Salamin *et al.*, "100 GHz Plasmonic Photodetector," *ACS Photonics,* vol. 5, no. 8, pp. 3291-3297, Aug. 2018.

[19] P. Ma *et al.*, "Plasmonically enhanced graphene photodetector featuring 100 Gbit/s data reception, high-responsivity and compact size," *ACS Photonics,* Nov. 2018.

[20] Y. Salamin *et al.*, "Microwave plasmonic mixer in a transparent fibre–wireless link," *Nature Photonics,* vol. 12, no. 12, pp. 749-753, Dec. 2018.

[21] Y. Salamin *et al.*, "Compact and ultra-efficient broadband plasmonic terahertz field detector," *Nature Communications,* vol. 10, no. 1, p. 5550, Dec. 2019.

[22] B. S. Dennis, M. I. Haftel, D. A. Czaplewski, D. Lopez, G. Blumberg, and V. A. Aksyuk, "Compact nanomechanical plasmonic phase modulators," *Nat. Photonics,* vol. 9, p. 267, 2015.

[23] C. Haffner *et al.*, "Nano–opto-electro-mechanical switches operated at CMOS-level voltages," *Science,* vol. 366, no. 6467, pp. 860-864, 2019.

[24] A. Emboras *et al.*, "Atomic Scale Plasmonic Switch," *Nano Letters,* vol. 16, no. 1, pp. 709-714, Jan. 2016.

[25] A. Emboras *et al.*, "Atomic Scale Photodetection Enabled by a Memristive Junction," *ACS Nano,* June 2018.

[26] A. Emboras *et al.*, "Electrically controlled plasmonic switches and modulators," *IEEE Journal of Selected Topics in Quantum Electronics (JSTQE),* vol. 21, no. 4, pp. 276-283, July/Aug. 2015.

[27] U. Koch, C. Hoessbacher, A. Emboras, and J. Leuthold, "Optical memristive switches," *Journal of Electroceramics,* journal article March 07 2017.

[28] A. Emboras *et al.*, "Nanoscale Plasmonic Memristor with Optical Readout Functionality," *Nano Letters,* vol. 13, no. 12, pp. 6151-6155, 2013/12/11 2013.

[29] C. Hoessbacher *et al.*, "The plasmonic memristor: a latching optical switch," *Optica,* vol. 1, no. 4, pp. 198-202, Oct. 2014.

[30] B. Cheng *et al.*, "Ultra compact electrochemical metallization cells offering reproducible atomic scale memristive switching," *Communications Physics,* vol. 2, no. 1, p. 28, 2019/03/07 2019.