Plasmonics for Signal Processing

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Abstract: We review some of the issues involved in using different plasmonic guided-wave structures for modulation, switching and filtering.

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1. Introduction

The field of integrated photonics has shown a remarkable development since its inception in the 60s, an inception partly fueled by the tremendous unfolding of integrated electronics. But some original vision of a sort of replacement of electronics never materialized, not surprising since the underlying physics is different, with bosons and fermions, respectively, involved. Thus, so far there does not exist any competitive RAM-type photonic memory, nor are there any convincing photonic digital signal processing devices, competitive with the remarkable and still continuing development of electronics. Integrated photonics has a limited but important scope in functions such as switching and routing in the space, time and wavelength domains as well as the usage of nonlinear optical function. However, the exponential increase in integration density since the 80s has been remarkable, Fig. 1 [1], and shown the potential of drastic improvements in size, power dissipation and cost in telecom as well as interconnect systems.

In recent years, this evolution has primarily been brought about by using silicon/air or quartz interfaces, giving a larger refractive index contrast than previously employed. To increase spatial integration, it is necessary to find a successor to the current silicon nanowire technology. Such successors seem to have to rely on materials with negative ε, notably metals since these offer a possibility for increasing the integration density in photonic lightwave circuits in two ways: (i) By using principles other than total internal reflection, i.e. plasmonics and (ii) employing e.g. metamaterials to generate artificially very large effective media refractive indices. Both methods could allow denser lateral packing of waveguides as well as shorter resonators and filters. A main and seemingly detrimental problem for many applications has been the optical loss that is associated with these metal based metamaterials. One way of mitigating this is to use amplification, e.g. in the form of QDs due to their potentially large gain.

The signal processing in photonics we are concerned with here are switching and modulation with applications in cross connects (OXCs), optical add-drop multiplexers (OADMs), wavelength space switches, and wavelength muxes and demuxes. We omit all processing involving storage, likewise concentrate only on the fabric between transmitter and receiver. In the latter two cases, plasmonics certainly has a role, such as in recently reported impressive nanolasers and usage for light concentrators in detectors. However, it is an open question whether the by definition small volumes of the nanolasers can supply the powers needed in complex optical networks.

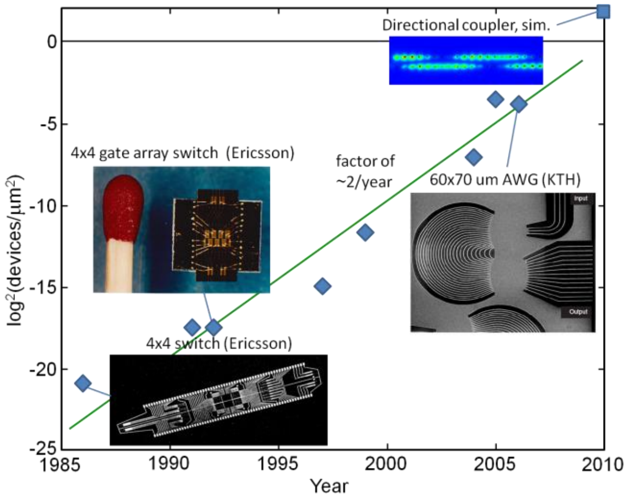

Fig. 1. A Moore's law for photonic integrated circuits [1]. The simulation result of the present paper is indicated by the blue square.

2. Devices based on near-field coupled nanoparticles

Waveguides made from arrays of near-resonantly operated and near-field coupled metal nanoparticles in the shape of e.g. spheres has attracted some attention [2,3]. Nanoarray waveguides, based on passive nanoparticles, such as silver nanoparticles are, however, very lossy, see e.g. Ref. 3, and are thus of limited use for some albeit not all applications. By operating the nanoparticles appropriately, radiation losses can be made small and basically only (the very large) losses due to Joule heating remain. However, in anticipation of a possible future breakthrough in developing metamaterials with at least a factor of 10 lower losses [4,5], or in achieving loss compensation [6]; we analyze in this paper the ability of two adjacent arrays of metal nanoparticles to achieve extremely compact directional couplers. Such couplers form the basis of generic types of integrated photonics devices. Specifically, here, the coupling length l_c, the spectral characteristics of the coupling, and switching characteristics are investigated.

The arrays consist of 50-nm diameter metal particles spaced by d=75 nm. The particle permittivity corresponds to lossless silver, which simplifies our analysis, facilitates good transmission, with only small radiative losses for waveguide k-numbers to the right of the light line in the host, cf. [3], here corresponding to $\lambda_0\approx358$-372 nm. A hybrid finite-element-method and multi-level fast-multipole-algorithm (FEM/MLFMA) is used to simulate the structure in the frequency-domain with 3D resolution of the particles. Placing two particle arrays in proximity with a center-to-center spacing of c=90-130 nm, we demonstrate a spatially periodic sinusoidal-like coupling of the surface plasmon polariton excitations on the arrays, Fig. 2(a). Extremely short coupling lengths, e.g. 490 nm for c=90 nm, are demonstrated, indicating a footprint of a directional coupler structure of only ~800×300 nm^2. The coupling length is about three orders of magnitude shorter than in conventional directional couplers based on usual dielectric materials, like silica or lithium niobate. In contrast to the case for dielectric waveguides, where the coupling length increases exponentially as the separation increases, here the coupling lengths of Fig. 2(a) can be very well fitted by a power of the spacing c of the nanoparticle arrays as $l_c(c)=l_0(c/d)^{5.6}$, l_0=170 nm. Further, we analyzed the impact of phase mismatch between the different waveguides. This can be brought about e.g. by artificially changing the plasma frequency or the host refractive index for one of the arrays. Again, the behaviour is very analogous to the conventional coupler and we see that for an approximately 1.4 μm long coupler, a change of the plasma frequency by 0.32% ($\hbar\omega_{p,lower}=6.18\rightarrow6.16$ eV) is enough for high extinction ratio switching, Fig. 2(b). The required switch energy is in the fJ-range. Directional couplers with the two nanoarrays offset by half a period, d/2, showed a stronger wavelength dependence of the coupling length, thereby enabling efficient filtering: 2.4 nm bandwidth for a 3 μm long coupler, indeed very good data for an integrated optics filter.

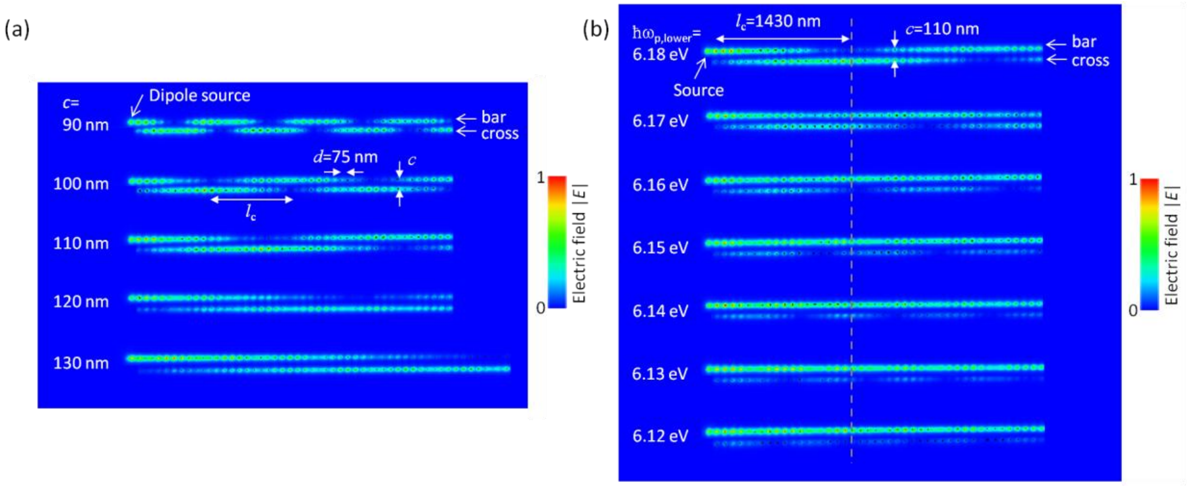

Fig. 2. Top view of coupled-nanoparticle-array devices showing the E-field magnitude in a plane 3 nm above the particle surfaces for the source wavelength λ_0=371 nm. (a) Directional coupler (b) Optical switch.

The possibilities to mitigate the losses by employing gain have been intensively researched recently. However, the losses involved for high confinement are very high and the consequently required gains are also large and appear to be on the verge of being realizable. Even if they are, there are serious issues regarding signal-to-noise ratio in real systems [7]. For the nanoarray devices analyzed here, loss can be mitigated by using a composite nanoparticle as in Fig. 3, where a negative-ε or metal shell surrounds a quantum dot (QD), with the QD barrier isolating the QD core from the metal. Optical pumping through the metal shell is assumed. With this arrangement, one can, using realistic data for the QD, in principle compensate the loss due to the metal and in addition obtain very intriguing dispersion properties [6].

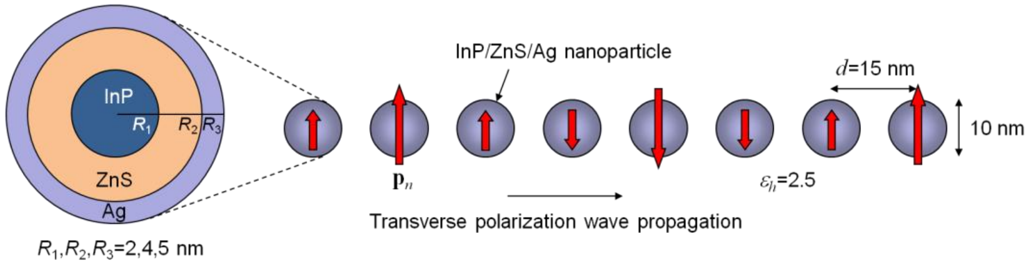

Fig. 3. Composite InP/ZnS/Ag QD/metal-shell nanoparticle-array waveguide with loss compensation [6].

3. Long-range plasmon high-confinement waveguide devices

As a contrast to the very high confinement structures discussed above, with losses in the range of 1-10s of dB/μm, there has been a huge volume of work on "long range plasmons", with concomitant lower confinement. An interesting example, where confinement in one dimension is traded for this property in the orthogonal dimension is described in [8]. In this metal/quartz/silicon/quartz structure, propagation lengths on the order of 100s of μm can be obtained with confinement on the order of 50nm laterally × 5nm in depth (~λ/300 × λ/30), but with a long tail extending into the silicon substrate, which, however does not hamper the lateral packing density or the design of very compact directional couplers. This structure can be used to construct directional couplers, ring resonators and 1x2 MMI couplers, around 1 μm long with outgoing waveguides separated by around 1 μm. However, propagation distances on the order of 100s of μm are in general bought at the price of lower confinement, and any “electronics”-like footprint will generally require near resonant operation, such as in the arrays described above.

4. Summary

It appears that in order to continue the scaling of integration density mentioned above one has to rely on materials with negative epsilon, notably metals, either in plasmonic type devices or to create a high index waveguide. We have analyzed devices, such as modulators based on high effective medium index metamaterial structure. The losses are comparable to corresponding conventional plasmonic devices, but other properties are quite unique. Results will be presented in the talk.

However, losses are still a main issue hampering complex circuits in telecom and especially interconnects. Thus, recent research in plasmonics has taken a turn towards other functions where more or less only stand alone devices are required, such as sensors, antennas, metamaterials, and field enhancements for SERS etc. However, a factor of 10 in longer photon lifetime in some negative epsilon material would change the agenda rather completely and open the gates for a whole family of efficient nanophotonics circuits, where the full impact of the small footprint and ensuing low control power dissipation mentioned above could be utilized to drastically change the outlook for integrated photonics. In addition to the processing functions mentioned above, which have been around for a considerable time, this would also open for a host of novel exciting plasmon mediated phenomena such as lossless plasmon transmission in near field coupled metal-quantum dot structures.

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