Stacked optical antennas

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We propose and analyze a stacked optical antenna (SOA). It is characterized by a stacked structure of its arms at the center, and an interstitial gap layer (IGL) in between, which plays the role of the feed gap. Because of its in-plane arrangement, the IGL can be fabricated by standard planar deposition techniques providing high accuracy and control. A SOA can be an enabling element for several technologies, in particular for optical detection, communication, and encryption besides applications in microscopy. © *2011 American Institute of Physics*. [doi:10.1063/1.3541544]

Optical antennas are devices that convert free-propagating optical radiation into localized energy and vice versa.[1] They define an enabling technology for the control and manipulation of optical fields on the nanometer scale. Optical antennas hold promise for enhancing the performance and efficiency of photodetection, light emission, nonlinear wave mixing, and sensing on the nanometer scale and on the single photon level.[2]

The gap of an optical antenna is the location of largest field intensity.[3–6] Its properties are therefore decisive for various applications in near field optics. The gap is characterized by its width, cross sectional area, and the properties of the gap medium.[7] The electric field inside the gap increases as the gap width is reduced.[8] Therefore, the gap has to be made as small as possible for many experiments. In addition, certain structures such as a fluorescent molecule or quantum dot should be positioned precisely inside the gap. These requirements can be satisfied with the proposed stacked optical antenna (SOA).

The SOA is characterized by a stacked structure at its center [c.f. Fig. 1(a)] and an interstitial gap layer (IGL) in between the two arms. This is in contrast to the so far considered planar optical antennas (POAs), which feature a lateral arrangement of the antenna and its elements.[3,5,6,9,10] However, the spectral and angular responses of SOA and POA are similar since both depend on the overall length and width of the antenna arms; the geometrical details of the overlap region introduce but minor changes.

The gap area of the SOA is defined by the degree of overlap of the antenna arms, typically 10–50 nm in both directions. The gap width can be any value (as long as it is small compared to the length of the antenna) down to atomic size and defined to atomic precision, for instance by molecular beam epitaxy (MBE). The material of the IGL can be applied by techniques known from semiconductor device manufacturing.

Figure 1(a) shows an example of such a SOA. It consists of two separate gold arms of length 80 nm, thickness 10nm, and width 10 nm. The two arms overlap near the feed region over a distance of 10 nm where they are separated by a 4 nm thick gap. The SOA is illuminated by a plane wave with wavelength $\lambda = 1060$ nm at normal incidence and polarized along the SOA axis. Figure 1(b) depicts the field distribution calculated by the finite difference time domain code for $\lambda = 1060$ nm and $\varepsilon_{Au} = -48 + i3.4$.

The field is strongly enhanced in the gap region. The intensity in the gap is more than a factor of 30 higher than the intensity at the extremities of the antenna, and four orders of magnitude higher than the intensity of the incident field. For comparison, Fig. 1(c) shows the field distribution for a POA consisting of the same elements as the SOA. The fields in the gap are similar, indicating that the SOA features all the desired properties of a standard gap antenna while enabling a simpler and more accurate fabrication process.

Figure 2 shows the calculated intensity enhancement in the center of the gap of the SOA shown in Figs. 1(a) and 1(b) as a function of wavelength λ. The spectrum features a resonance at $\lambda = 1060$ nm. The field in the gap and its spectral dependence can be tuned by the antenna geometry, such as the antenna arm length[11] and the antenna profile. For example, the antenna can be shaped into a bow-tie geometry[5,9] or any other antenna geometry. Recently, planar metal-dielectric-metal structures have also been explored for the fabrication of plasmonic nanogap resonators.[12]

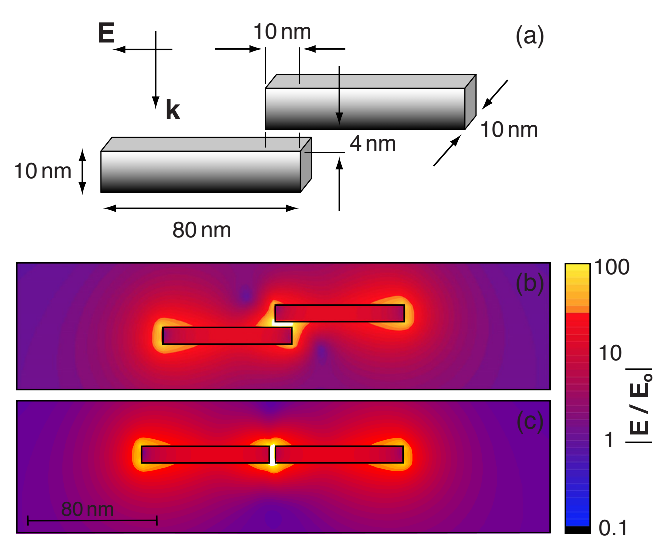

FIG. 1. (Color online) Basic configuration of a SOA and dimensions used for theoretical analysis. (b) Calculated field distribution near the SOA characterized in panel (a). (c) Calculated field distribution near a planar optical antenna with similar arms and gap. The antennas are irradiated by a plane wave at normal incidence with wavelength $\lambda = 1060$ nm. Logarithmic scaling.

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In the following sections, the potential of the SOA with IGL will be described in detail for a few examples. They are based on the qualities of the IGL:

(1) The IGL can be any material suitable for evaporation, in particular MBE, or other thin film deposition techniques.
(2) The IGL can be composed of different materials even, for instance, a *p*- and an *n*-semiconductor, forming a *p*-*n* or a *p*-*i*-*n* junction in between.
(3) The gap width is precisely adjustable down to the atomic level.
(4) Any electronic process, including fluorescence, is fast because of short distances within the IGL and coupling to the optical antenna.
(5) The IGL is protected on top and bottom by the metal of the antenna arms.

When the IGL consists, for example, of a material with large optical nonlinearity (NL), the SOA becomes a frequency mixer element emitting, for example, at $\nu_{3\pm} = \nu_1 \pm \nu_2$ when hit by waves at frequency ν_1, ν_2. In principle, any nonlinear process can be exploited, with applications ranging from low-frequency electro-optics to wave mixing[13] and high harmonic generation.[14,15] Note that phase-matching, co-linearity, and high transparency are not required due to the subwavelength dimensions of the IGL; this allows a much wider selection of materials with large nonlinear susceptibilities χ^{NL}.

The small size of the IGL in the gap favors the incorporation of just one quantum dot, molecule, or defect center. This is a prerequisite for the emission of single photons[16] or entangled photon pairs[17] as needed in optical communication and encryption.

Further functionality arises if the arms of the SOA are contacted to a voltage source (dc or low frequency ac) or a detector network (Fig. 3). Contacting by transparent (e.g., indium tin oxide) wires, by attaching thin opaque wires to optically neutral points on the arms, or by induction of the arms from neighboring wires will not disturb the optical antenna effect. In such a configuration, the IGL can function as the gap of a tunneling junction, capable of feeding current-induced light into the lobes of the antenna or light-induced current into its arms.[18,19] The charge transfer across the IGL can be further controlled by molecules, quantum dots, or *p*-*n* type structures with strong charge-transfer transitions.[20] Fabrication of such tunneling junctions requires precision down to the atomic level, for which the SOA geometry with its planar gap structure offers clear fabrication advantages over in-plane antennas. The small thickness of the IGL reduces losses of photocurrent on the way to/from the electrodes[21] and increases the speed of emission, respectively, of current generation in the photoelectric element. For both cases, the speed is further increased by an optimally adapted antenna. Last, for organic light-emitting diode material, the protection of the active layer by the arms of the SOA may be beneficial for its stability.

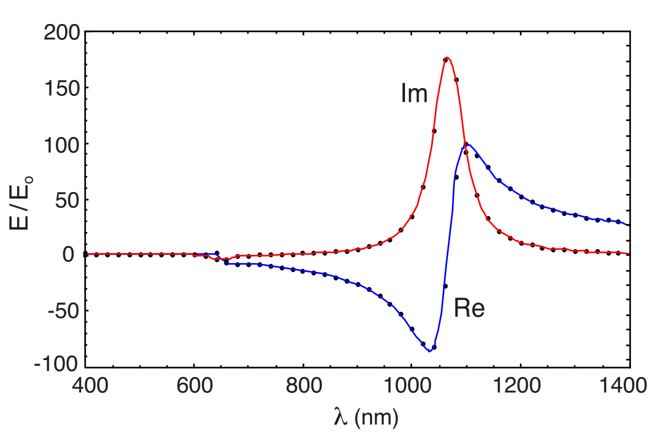

FIG. 2. (Color online) Wavelength dependence of the electric field enhancement in the gap of the SOA. The curves correspond to Re$\{E/E_o\}$ and Im$\{E/E_o\}$, respectively, with E_o being the incident field.

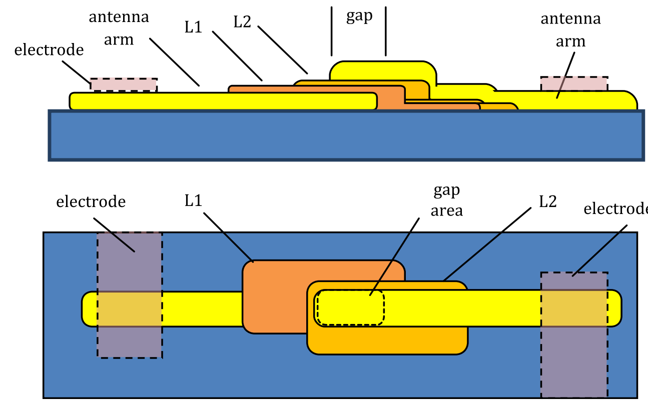

FIG. 3. (Color online) Schematic illustration of a SOA with bilayered (L1,L2) IGL, for instance a *p*- and a *n*-semiconductor. The overlap of the two arms defines the gap region. Electrodes are optional. Top: side view; bottom: top view.

In conclusion, the SOA offers a large choice of materials and dimensions for the interstitial gap layer. Depending on the IGL material, a SOA can interact in various ways with light waves. When connected to an electrical network, electro-optic and photoelectric effects can be exploited. The SOA with IGL hence considerably enlarges the range of applications of optical antennas.

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