COMMENTARY

Plasmonics: the future wave of communication

Jagmeet Singh Sekhon and S. S. Verma

Plasmonics offers the potential of developing a communication device with a diffraction limit in the range of present-day electronic microprocessors and data carrying capacity equal to that of photonic devices. This study represents a comprehensive introduction to the various physical mechanisms that generate surface plasmons and their applications. The progress and future prospects of plasmonics particularly as a next generation of wave communication is reviewed highlighting the significant challenges in achieving it.

Currently, electronics (flow of charge) is important in the field of communication. According to principle, higher the frequency, larger the data transfer rate; when frequency of electronic pulse increases, the electronic device get hot and wires becomes very lossy. Hence, huge amount of data transfer by electronics is not possible. Further, to miniaturize the size of a electronic device, when the lateral size of electronic wires is reduced; the resistance (inversely proportional to area of cross-section of wire) is increased, but the capacitance of the wire remains almost the same which is responsible for the time delay (RC effect)[1,2].

In laboratories, photonics are replacing electronics, wherever high data transfer rate is required. In photonics, an optical fibre transmits optical signal along its axis by a process called total internal reflection. The fibre consists of a core surrounded by a cladding layer, both of which are made of dielectric materials. To confine the optical signal in the core, the refractive index of the core must be greater than that of the cladding. The lateral confinement size of the optical cable is approximately half the wavelength of the light signal passing through it and is called diffraction limit[3]. Although, the data transportation rate is high in photonics, owing to the diffraction limit, the size of optical fibre is in the order of hundreds of nanometres much larger than the present-day nano-electronic devices. In the increasing quest for transporting huge amount of data at high speed along with miniaturization, both electronics and photonics are facing limitations. It is difficult to cobble them to obtain a high bit rate along with miniaturization owing to their mismatched capacities and sizes.

Researchers are promoting plasmonics as the future of wave communication. The confinement of light wave on the dimensions of metal below the diffraction limit forms a major part of the application of plasmonics in communication. Plasma, the fourth state of matter contains free positive and negative ions. Plasmonics – the science of electron cloud oscillation (plasma oscillation) in metal and semiconductor, in response to the irradiated light and plasmon is a quantum of this plasma oscillation[4]. Thus, plasmon[5] is a quasi-particle resulting from the quantization of plasma oscillations just as photon is quantization of light. When light falls on a metal, owing to the electric field component of light, the conduction electron cloud of the metal shifts and results in the deficiency of negative charge on the opposite side. Due to coulomb attraction, the electron cloud rebounces to its original position, but owing to inertia it gets overshot resulting in a oscillation frequency called surface plasmon resonance frequency, which is equal to the frequency of irradiated light. Besides, application of plasmonics in the field of nanosensing[6–8], spectroscopy (surface-enhanced Raman spectroscopy)[9–11], cancer therapy[12] and clocking devices[13,14] is being explored.

There are two main components of plasmonics: (i) surface plasmon (SP) polaritons and (ii) localized surface plasmons (LSPs). SPs are associated with surface charge oscillation having frequency almost equal to light. The energy required to receive and send a SP pulse can be less than that needed for the electric charging of a metallic wire. This could allow the plasmons to travel along nanoscale wires (called interconnects) to carrying information from one part of a microprocessor to another with high bit rate. Plasmonic interconnects would be a great boom for chip designers, who have been able to develop ever smaller and faster transistors that can move data quickly across the chip. Plasmon-based waveguides are not only a mode by which light can be guided on nanoscales, but also promise a path for chip scale device integration[15,16]. Here, we provide a qualitative discussion on the factors that manage plasmon excitation by different methods along with a brief description on some theoretical aspects of plasmonics. The article ends with a concise dialogue on promising applications of plasmonics in communication. It is hopeful that this will inspire detailed study of plasmonic devices in the field of communication.

Surface plasmon excitation

Plasmonic structures can exert huge control over light waves at the nanoscale. As a result, energy carried by plasmons allow for light localization in ultrasmall volumes, far beyond the diffraction limit. To generate the SPs, it is necessary to excite the metal – dielectric interface (Figure 1 *a*) in which the dielectric constant of the metal is a function of frequency and possesses a negative real part. Experimentally, to excite the SPs, a major milestone was achieved by the studies of Otto and Kretschmann in which a prism is introduced to match the photon and surface plasmon wave vectors[17–19]. The plasmon losses are lower at the interface between a thin metal film and a dielectric than inside the bulk of the metal film (Figure 1 *b*) because the field spreads into the nonconductive materials, where there are no free electrons to oscillate, and hence no energy dissipation owing to collisions. This property naturally confines plasmons to the metallic surface neighbouring the dielectric; in a sandwich with dielectric and metal layers.

The Maxwell's equation under appropriate boundary conditions[20] gives SP wave vector

$$K_{\mathrm{sp}} = K_0\sqrt{\frac{\varepsilon_{\mathrm{d}}\varepsilon_{\mathrm{m}}}{\varepsilon_{\mathrm{d}}+\varepsilon_{\mathrm{m}}}}$$

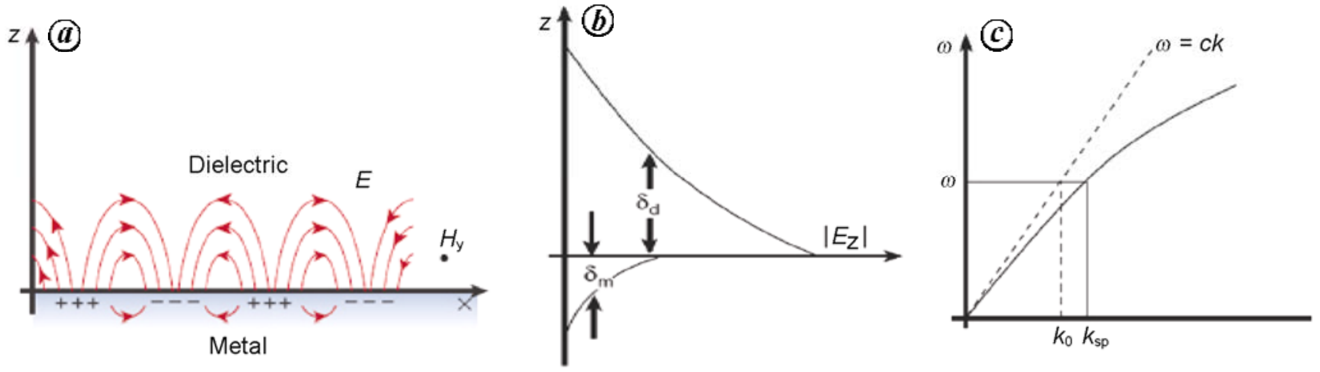

Figure 1. ***a***, Surface plasmons on the metal dielectric interface. ***b***, Propagation distance in the metal and dielectric medium. ***c***, Dispersion curve showing the higher SPs wave vector than the light wave in free space. Figures are taken from ref. 22.

with ε_d and ε_m as the dielectric constant of host medium and metal respectively, and K_0 is wave vector of light wave in the host medium/vacuum. Hence, wave vector of SPs on the metal dielectric interface is always greater than the wave vector of light wave in free space (Figure 1 *c*). Therefore, it is not possible to couple light waves directly with SPs.

In Otto configuration[17], the metal surface is separated by an air or dielectric gap at a distance of sub-micrometre from the prism. The resonant excitation of SPs is achieved on the metal surface through the gap where the evanescent fields from both sides of the gap overlap. The Kretschmann–Raether configuration[17,20] – a finite thickness of the metal layer directly attached to the base of the prism is more versatile because it is experimentally less difficult to realize. The thickness influences the coupling angle, as well as the coupling efficiency. It is generally a result of the destructive interference between the partially reflected light wave from the prism/metal interface and the re-radiated light wave from the metal/dielectric interface. Various shapes of prism (triangular, half cylinder and hemisphere) can be used for exciting SPs.

In grating coupling method, a metallic grating with period *d* embedded in a dielectric medium possessing dielectric constant ε_d has been used for momentum matching, and this condition[18] is given by

$$K_{sp} = K_0 \sin\phi_0 + K_{grat} = \left(\frac{\omega}{c}\right)\varepsilon_d^{\frac{1}{2}}\sin\phi_0 \pm \frac{2\pi m}{d}, \tag{1}$$

where *m* is an integer. Thus, launching the SPs wave on metallic surface in grating coupling is incident angle (ϕ_0)-dependent. An alternative method[21] is the utilization of a localized object, such as the tip of a surface near-field optics microscope or a defect deposited on the interface, which diffracts an incoming wave in many components, both propagating and evanescent: a part of these waves matches the excitation condition of the SP.

SPs can also be excited by a light wave guided in an optical waveguide[19]. In a waveguide, light propagates in the guiding mode form. The electromagnetic (EM) field of a guided mode is concentrated in the wave-guiding layer, and a portion of the field propagates, as an evanescent wave, in the low-refractive index medium surrounding the wave-guiding layer. When light enters the region of the waveguide containing a metal layer, the evanescent wave excites SPs at the outer boundary of the metal layer. The coupling condition for the guided mode and the SP is fulfilled when the propagation constants of the two waves are equal.

$$K_{\text{mod}\,e} = \text{Re}\{K_{sp}\}, \tag{2}$$

where $K_{\text{mod}\,e}$ and K_{sp} denotes the propagation constant of the waveguide mode and SPs respectively.

The excitation of SP leads to the build up of an enhanced essentially two-dimensional optical field propagating in a plane at the interface and confined perpendicular to it in the so-called near-field zone. In the near-field zone, EM field decays evanescently into the dielectric and conducting media and is a consequence of bound and non-radiative nature of SPs, which prevents power from propagating away from the surface (Figure 1 *b*). Once the SPs are excited on the surface of a flat metal surface, they start propagating along the metal dielectric interface but gradually attenuate owing to losses arising from absorption in metal and depend on the dielectric function of the metal at resonance frequency. The propagation length is obtained from the expression[22]

$$\delta_{sp} = \frac{1}{2K_{sp}} = \frac{c}{\omega}\left(\frac{\varepsilon'_m + \varepsilon_d}{\varepsilon'_m \varepsilon_d}\right)\frac{(\varepsilon'_m)^2}{\varepsilon''_m}. \tag{3}$$

In metallic nanoparticles of diameter less than 30 nm, scattering processes are usually negligible and particles absorb energy. The following mechanisms[23] are responsible for absorption: (i) collective excitations of the free electrons; (ii) electronic transitions of bound electrons from occupied to empty bulk bands of different indexes and (iii) surface dispersion or scattering of free electrons. The first two mechanisms are fundamentally absorption-related. In contrast, surface scattering is one of the several mechanisms for dissipating energy already absorbed by the SP resonance. For all these considerations, the dielectric function modifies as

$$\varepsilon(\omega,r) = \varepsilon_{\text{bulk}}(\omega) - \varepsilon_{\text{free}}(\omega) + \left[1 - \frac{\omega_p^2}{\omega\{\omega + \iota\omega_d + \iota\omega_d(r)\}}\right], \tag{4}$$

where $\varepsilon_{\text{bulk}}(\omega)$ is measured bulk dielectric function given by the sum of the contribution from the free electrons and $\varepsilon_{\text{free}}(\omega)$ is represented by the Drude model. ω_d is the damping constant owing to the dispersion of electrons by the ions, and $\omega_d(r)$ is the damping term owing to the surface dispersion of the electrons which is size dependent.

An analytical solution of Maxwell's equations for the scattering of EM radiation by spherical particles is given by Mie[24]. The limitation of the Mie theory[24] is that the dielectric constant of the nanoparticles is taken from the bulk but it is size dependent. When the size of particle is much smaller than the wavelength of incident light, the nanoparticle defects a field that is spatially constant but with a time-dependent phase known as the quasistatic limit[23]. In this limit, charge displacement in a sphere is homogenous yielding a dipolar charge distribution on the surface, which is equal to first-order Mie calculation. The particles absorb energy by the excitation of SP resonance. The single particle polarizability is given by

$$\alpha_{\mathrm{sph}} = 4\pi a^3 \frac{\varepsilon_{\mathrm{m}} - \varepsilon_{\mathrm{d}}}{\varepsilon_{\mathrm{m}} + 2\varepsilon_{\mathrm{d}}}, \tag{5}$$

where ε_{m} and ε_{d} are dielectric functions of material and the host medium respectively, and a the radius of the spherical body.

The non-spherical nanoparticles are attracting much attention in comparison to the spherical particles because of two distinct plasmon resonances related to the longitudinal and transverse modes. An extension of Mie theory with an added geometrical factor is called Gans theory[25] to study the plasmonic properties of ellipsoids, the LSP resonance split into longitudinal and transverse. The particle depolarization factor along the three axes of the ellipsoid is given below.

$$\alpha^{(a)} = \frac{1-\eta^2}{\eta^2}\left[\frac{1}{2\eta}\ln\left(\frac{1+\eta}{1-\eta}\right) - 1\right] \tag{6}$$

and

$$\alpha^{(b)} = \alpha^{(c)} = \frac{1-\alpha^{(a)}}{2}, \tag{7}$$

with $\eta = \sqrt{1-(b/a)^2}$ and α is the depolarization factor for the corresponding axes a, b and c.

An application of the plasmonic effect is that by arranging metallic nanostructure in different geometries, one can guide light below the diffraction limit at visible frequencies. The main goal of this research is to study basic interactions between dipole plasmons in metallic nanostructures. Different mechanisms of such interactions are studied including near-field (dipole) interaction between neighbouring metallic nanoparticles (dipole–dipole) and far-field interaction (antenna-like). Weber and Ford[26] developed a dispersion relation for a chain of nanoparticles whose radius is a and interparticle spacing is d which is given as below for infinite chain length.

Transverse

$$\frac{\omega^2}{\omega_0^2} = 1 + 2\frac{a^3}{d^3}\sum_{j=1}^{\infty}\frac{\cos jkd}{j^3} \tag{8}$$

Longitudinal

$$\frac{\omega^2}{\omega_0^2} = 1 - 4\frac{a^3}{d^3}\sum_{j=1}^{\infty}\frac{\cos jkd}{j^3}. \tag{9}$$

In a chain of nanoparticles with centre-to-centre separation in the order of nanometres, near-field interaction between the particles dipole dominates. Hence, such an array of nanoparticles can guide EM energy via near-field dipole coupling upon local excitation at particle resonance frequency. Weber and Ford[26] also report the dispersion relations for a finite chain.

Plasmonics in communication

According to new research scientists, in the field of plasmonics a study of the interaction of light with metallic nanostructures will make it easier to design new optical material devices. The primary goal of this field is to develop new optical components and systems that are of the same size as the present-day smallest integrated circuits. The next step will be to integrate the components into an electronic chip to demonstrate plasmonic data generation, transport and detection. The behaviour of plasmon waves on metals is similar to that of light waves on glass in multiplexing or sending multiple waves. Plasmon sources, detectors and wires as well as splitters and even plasmonsters can be developed. Applications mainly depend on controlling the losses and the cost of nanofabrication techniques. Finally, plasmonic nanocircuits combine a high bandwidth with a high level of compaction and make plasmonic components useful in making optical circuits. Plasmon can ferry data along computer chips for which plasmonic switches are also required. The building block for pure plasmonic circuit for communication includes light source, collimator, waveguide, switch which are discussed briefly in this section. Further, applications include resonator, detectors, splitter, multiplexer, cavity, etc.

Plasmonic lasers

Researchers are now on the verge of inventing a nano-laser. In the ordinary laser, the diffraction limit restricts the size of laser to less than half the wavelength of light, that is its size not less than hundred of nanometres for visible range of light. If the diameters of the mirrors are smaller than half the wavelength of light, then the light will not bounce neatly between the mirrors and diffract which results its spread out. The plasmonic wave properties of subwavelength will be useful for making a nano-laser. Recently, Zhang and coworkers[27] demonstrated a micrometre-long and nanometre-wide cadmium sulphide wire on a silver surface with 5 nm thick insulating gap that had been coated with nanometres of magnesium fluoride. Nanowire is targeted with light of wavelength 405 nm to emit photons. Most of these photons produced SPs, which bounced back and forth between its ends. Just as in an ordinary laser, the plasmons stimulate the atoms in the cadmium sulphide to emit more light, which in turn produced more plasmons in a runaway process. Some of the energy of the plasmons emerged from the ends of the channel as laser light with a wavelength of 489 nm. The channels in the device are as little as 50 nm × 5 nm much smaller than the roughly 245 nm diameter of a conventional laser of a similar wavelength. In another study[28] 44 nm sphere of silica with 14 nm gold core acts as SP amplification by stimulated emission of radiation (SPASER)-based nano-laser. Light shining on a suspension of such spheres was able to excite slightly different plasmons that do not travel on the surface of the sphere. They found that in each sphere, the plasmons could stimulate the production of still more plasmons and hence, the emission of light transformed each individual onto a small laser.

Plasmonic collimator

Plasmonic collimation provides a means of efficiently coupling the output of a variety of lasers into a waveguide. Plasmonic collimator is based on the high-directional emission from sub-wavelength aperture surrounded by surface wrinkles. The process is carried out by coupling laser emission from a sub-wavelength aperture with SPs propagating along the laser facet patterned with second-order grating. Radiations from grating grooves and the aperture interfere constructively in the far field leading to greatly reduced divergence as compared to ordinary laser. The aperture and grooves in the plasmonic collimator act as an array of coherent light sources. Yu *et al.*[29] show a great reduction in laser beam divergence by using quantum cascade lasers as a model system. Divergence angles as small as 2.4° that represent a reduction in beam spread by a factor of 25 compared with the original 9.9 mm wavelength laser used in the model were obtained.

Plasmonic waveguides

The plasmonic waveguide operating in various parts of the spectrum, i.e. ranging from visible to far-infrared region, is attracting much attention. Several metrics such as propagation distance, confinement mode, quality factor, group velocity and distance from light line for plasmonics waveguides have been proposed and analysed. There are several choices of plasmonics waveguide such as metal cylinder of circular cross-section[30], coupled metal nanoparticles[31–33], wedge-shaped waveguides[34], channel in metal surfaces[35] that may be useful in information technology applications.

(i) To achieve light wave propagation below the diffraction limit, it is suggested that light energy can be guided along a chain of closely spaced metal nanoparticles that convert optical signal to non-radiating SPs. The light energy transport along the chain of metal nanoparticle relies on the near-field electrodynamic interaction between metal particles that set up coupled dipole or plasmon mode. Brongersma *et al.*[32] proposed that light energy could be transported below the diffraction limit with high efficiency and group velocity greater than 0.1*c* along a wire of its characteristic length 0.1λ. Maier *et al.*[33] experimentally observed that most efficient frequency for transport is 3.19×10^{15} rad s^{-1} with a corresponding group velocity of 4.0×10^{6} m s^{-1} for longitudinal mode of plasmon waveguide having an inter-particle distance of 75 nm. The achieved bandwidth was calculated to be 1.4×10^{14} rad s^{-1}. In a chain of closely spaced nanostructures, the propagation distance depends upon the shape, nature of materials and separation between them and the dielectric constant of the host medium.

(ii) A plasmon could travel as far as several micrometres in the slot waveguide – far enough to convey a signal from one part of a chip to another. The plasmon slot waveguide squeezes the optical signal and shrinks its wavelength. Dionne *et al.*[36] have constructed slot waveguides that can support both transverse electric and transverse magnetic photonic polarization. The loss in slot waveguide can be minimized (leading to lossless materials) by using a low refractive index material[37], for example; a 100 nm thick Ag/SiO$_2$/Ag slab waveguide sustains the signal propagation up to 35 μm at wavelength of 840 nm. Feng *et al.*[38] observed that field localization could be improved by introducing the partial dielectric filling of metal slot waveguide, which also reduces the propagation losses. Channel in metal surface waveguide[35] supports the SPs at telecommunication wavelength with very low loss (having propagation length 100 μm) and well confined.

(iii) Boltasseva *et al.*[34] suggested that a triangular metal wedge can guide SPs at the telecommunication wavelength. It is experimentally observed that 1.43–1.52 μm wavelength can propagate a distance ~120 μm with confined mode width of ~1.3 μm along a triangular 6 μm high gold wedge with an angle of 70.5°.

(iv) Thin metal strip supports long-range surface plasmons. Ju *et al.*[39] experimentally confirmed that long range SPs could transfer data signal. It is demonstrated that 10 Gbps signal is transmitted over thin metal strip of 14 nm thick, 2.5 μm wide and 4 cm long gold strip. To reduce propagation loss, Kim *et al.*[40] fabricated a low-loss long-range SP waveguide in an ultraviolet-curable acrylate polymer having low refractive index and absorption loss. A 14 nm thick and 3 μm wide metal strip cladding in acrylate polymer material shows a loss of 1.72 dB/cm. Zia *et al.*[41] obtained a numerical solution by using the full vectorial magnetic field-finite difference method (FVH-FDM) for 55 nm thick and 3.5 nm wide strip on glass at the wavelength of 800 nm and noted that the SPs are supported on both sides of the strip and can propagate independently.

(v) Ditlbacher *et al.*[42] reported that metallic nanowires could provide lateral confinement below the diffraction limit. Nanowires have larger attenuation than planer films but light transport over a distance of several microns have been demonstrated.

Thus, a judicious choice of waveguiding geometry is necessary.

Plasmonic switches

Plasmonics may pave the way for computers that operate faster, store more information than electronically-based systems and are smaller than optically-based systems. Computer is a machine that can say 'yes/no' multiple times to transfer information. The motion of a molecule can serve the same purpose as an on–off switch. Plasmonic switch (sometimes called molecular machines) is created from switchable bistable-rotaxanes (a smart molecule), complex molecules that consist of a dumbbell shape with a ring or rings encircling the shaft. The ring can either move from one end of the barbell to the other or rotate around the shaft. This change in molecular shape is the basis of such a switch. These plasmonic switch are not yet part of a circuit[43]. Atwater[4] recently developed low-power versions of 'plasmonster' switches – a three-terminal plasmonic device with transistor-like properties. Plasmonsters can serve as the core of an ultrafast signal processing system, which could revolutionize computing and make plasmonic devices faster and useful. It is also suggested that applications such as YouTube having low resolution could be improved to obtain high-resolution images[43].

Summary

The excitation of SPs is mostly performed using far-field optical techniques, which have a resolution that is larger than plasmonic phenomena. However, for true nanoscale plasmonic studies, SPs point source with nanoscale dimensions and efficient excitation with nanoscale resolution are required. In addition fundamental processes to determine the losses of SPs need to be understood. Research is needed to reduce the limiting factor (loss) in plasmonics – which arises owing to many processes including radative damping, electron confinement, structural imperfections and metal heating losses.

---

1. Convey, J. A., Sahni, S. and Szkopek, T., *Opt. Express*, 2007, **15**, 4474–4484.
2. Zia, R., Schuller, J. A., Chandran, A. and Brongersma, M. L., *Mater. Today*, 2006, **9**, 20–27.
3. Maier, S. A., *IEEE J. Sel. Topics Quant. Electron.*, 2006, **12**, 1671–1677.
4. Atwater, H. A., *Sci. Am.*, 2007, **296**, 56–63.
5. Maier, S. A., *Plasmonics: Fundamental and Applications*, Springer.
6. Enoch, S., Quidant, R. and Badenes, G., *Opt. Express*, 2004, **12**, 3422–3427.
7. Sekhon, J. S. and Verma, S. S., *Plasmonics*, DOI: 10.1007/s11468-010-9182-3 (in press).
8. Sekhon, J. S. and Verma, S. S., *Plasmonics*, DOI: 10.1007/s11468-011-9206-7 (in press).
9. Kneipp, K., Wang, Y., Kneipp, H., Perelman, L. T., Itzkan, I., Dasari, R. R. and Feld, M. S., *Phys. Rev. Lett.*, 1997, **78**, 1667–1670.
10. Xu, H., Aizpurua, J., Käll, M. and Apell, P., *Phys. Rev. E*, 2000, **62**, 4318–4324.
11. Gopinath, A., Boriskina, S. V., Reinhard, B. M. and Negro, L. D., *Opt. Express*, 2009, **17**, 3741–3753.
12. Jain, P. K., El-Sayed, I. H. and El-Sayed, M. A., *Nanotoday*, 2007, **2**, 18–29.
13. Pendry, J. B., Schurig, D. and Smith, D. R., *Science*, 2006, **312**, 1780–1782.
14. Shalaev, V. M., *Nature Photon.*, 2007, **1**, 41–48.
15. Kim, J. T., Ju, J. J., Park, S., Kim, M., Park, S. K. and Lee, M., *Opt. Express*, 2008, **16**, 13133–13138.
16. Brongersma, M. L., Zia, R. and Schuler, J., *PIERS Online*, 2007, **3**, 360–362.
17. Dawson, P., Retrieved from http://www.qub.ac.uk/schools/SchoolofMathematicsandPhysics/con/plasmon/sp1.html
18. Dragoman, M. and Dragoman, D., *Progr. Quantum Electron.*, 2008, **32**, 1–41.
19. Homola, Jiri, *Chem. Rev.*, 2008, **108**, 462–493.
20. Evans, B., Retrieved from http://benjaminevans.net/files/surface_plasmons.pdf
21. Leveque, G. and Martin, O. J. F., *Proc. SPIE*, 2005, **5927**, DOI: 10.1117/12.616976.
22. Barnes, W. L., Dereux, A. and Ebbesen, T. W., *Nature*, 2003, **424**, 824–830.
23. Zhang, J. Z. and Noguez, C., *Plasmonics*, 2008, **3**, 127–150.
24. Mie, G., *Ann. Phys*., 1908, **25**, 377–445.
25. Qiu, L. *et al.*, *IEEE J. Sel. Topics Quant. Electron.*, 2007, **13**, 1730–1738.
26. Weber, W. H. and Ford, G. W., *Phys. Rev. B*, 2004, **70**, 125429.
27. Oulton, R. P. *et al.*, *Nature Lett.*, 2009, **461**, 629.
28. Noginov, M. A. *et al.*, *Nature Lett.*, 2009, **460**, 1110.
29. Yu, N. *et al.*, *Nature Photon.*, 2008, **2**, 564.
30. Pfieffer, C. A., Economou, E. N. and Nagi, K. L., *Phys. Rev. B*, 1974, **10**, 3038–3051.
31. Maier, S. A., Kik, P. G., Atwater, H. A., Meltzer, S., Harel, E., Koel, B. E. and Requicha, A. A., *Nature Mater.*, 2003, **2**, 229–232.
32. Brongersma, M. L., Hartman, J. W. and Atwater, H. A., *Phys. Rev. B*, 2000, **62**, R16356.
33. Maier, S. A., Brongersma, M. L., Kik, P. G. and Atwater, H. A., *Phys. Rev. B*, 2002, **65**, 193408.
34. Boltasseva, A., Volkov, V. S., Nielsen, R. B., Moreno, E., Rodrigo, S. G. and Bozhevolnyi, S. I., *Opt. Express*, 2008, **16**, 5252–5260.
35. Bozhevolonyi, S. I., Volkov, V. S., Devaux, E. and Ebbesen, T. W., *Phys. Rev. Lett.*, 2005, **95**, 046802.
36. Dionne, J. A., Lezec, H. J. and Atwater, H. A., *Nano Lett.*, 2006, **6**, 1928–1932.
37. Khurgin, J. B. and Sun, G., *Appl. Phys. Lett.*, 2010, **96**, 181102–181105.
38. Feng, N.-N., Brongersma, M. L. and Negro, L. D., *IEEE J. Quant. Electron.*, 2007, **43**, 479–485.
39. Ju, J. J., Kim, M., Park, S., Kim, J. T., Park, S. K. and Lee, M., *ETRI J.*, 2007, **29**, 808–810.
40. Kim, J. T., Park, S., Ju, J. J., Park, S. K., Kim, M. and Lee, M., *IEEE Photon. Technol. Lett.*, 2007, **19**, 1374–1376.
41. Zia, R., Selker, M. D. and Brongersma, M. L., *Phys. Rev. B*, 2005, **71**, 165431.
42. Ditlbacher, H. *et al.*, *Phys. Rev. Lett.*, 2005, **95**, 257403.
43. Plasmonics nanoswitches may expand laptop capacity a millionfold, Retrieved from http://x-journals.com/2009/plasmonics-nanoswitches-may-make-laptops-a-million-times-better/#more-1677

Jagmeet Singh Sekhon and S. S. Verma are in Department of Physics, Sant Longowal Institute of Engineering and Technology Longowal, Sangrur 148 106, India.*
**e-mail: jagmeetsekhon@ymail.com*