feature article

Surface-plasmon circuitry

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Electromagnetic waves at the surface of a metal have the enormous bandwidth of a light pulse and can be channeled into circuit components smaller than the diffraction limit.

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The advent of telecommunication over a century ago spurred an interest among scientists in surface waves. As early as 1907, while researching wireless telegraphy, Jonathan Zenneck analyzed the propagation of electromagnetic waves over extended metal surfaces.[1] Fifty years later, the possibility that metals support surface waves was revisited in the context of elementary excitations in solids. Rufus Ritchie predicted that fast-moving charged particles could excite surface waves in metal foils in addition to bulk plasma oscillations.[2] That was soon confirmed by experiments, and the term surface plasmon (SP) was born (see box 1). At the time, probably few would have expected SPs to generate the tremendous interest that they do today, all the way from quantum optics and data storage to spectroscopy and medicine.

In the early 1960s, SPs were mainly of academic interest until researchers realized that the intense electromagnetic fields associated with SPs generated in the vicinity of a metal interface could be used for sensing small dielectric-constant changes associated with the adsorption of molecules on the surface. Those fields were also found to be at the heart of the enormous enhancement in the Raman spectra, which today allows researchers to resolve the chemical structure of materials even at the scale of single molecules (see the article by Katrin Kneipp in PHYSICS TODAY, November 2007, page 40). In photonics, however, SP modes were seen more as a nuisance—a source of energy loss by absorption into the metal.

In the past decade, technological developments and the demonstration of novel SP-induced phenomena have changed that perception. In particular, modern nanofabrication and characterization techniques have made it possible to structure metal surfaces—to steer and control the flow of SPs—and to map features of that flow with unprecedented detail. Researchers soon realized that SP-based waveguides could transport the same huge bandwidth of information as in conventional photonics and yet not be limited by diffraction to submicron cross sections. In the effort to achieve that tantalizing vision and combine the compactness of an electronic circuit with the bandwidth of a photonic network, tackling the inevitable propagation losses became a pressing issue for practical devices and circuits.

Here we will focus on the tremendous potential of SPs for photonic circuitry and discuss the issues and challenges that scientists in the field are facing. (For a review of the extensive literature, see references 3–6.) The ongoing research efforts can be separated into three related subjects: SP-enhanced standalone devices, such as filters and sensors; devices that control SPs, such as waveguides; and actual SP circuits. While much work is under way to improve SP stand-

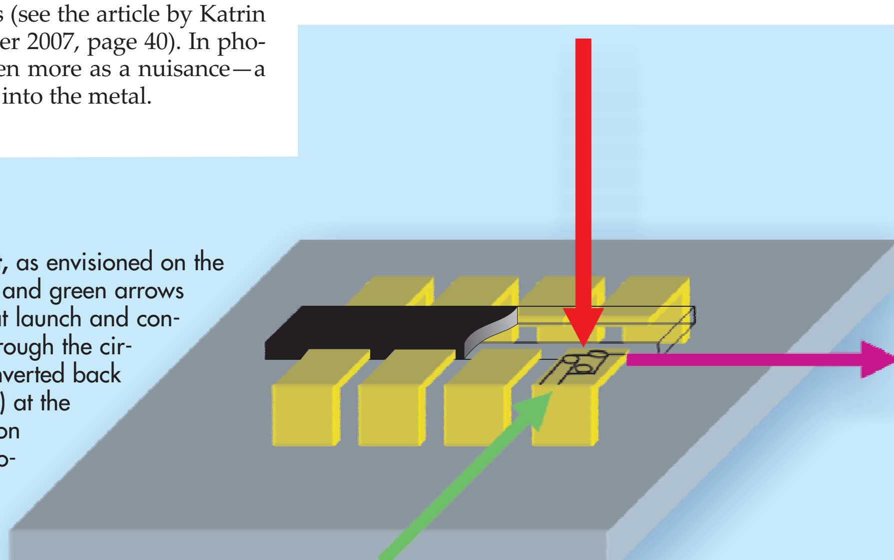


Figure 1. Surface-plasmon circuit, as envisioned on the leg of an electronic chip. The red and green arrows represent incident light beams that launch and control the propagation of the SPs through the circuit. Those SPs would then be converted back to a light beam (the purple arrow) at the circuit's output. The circuit's function could be, for instance, the synchronizing of several chips lying next to each other on a board.

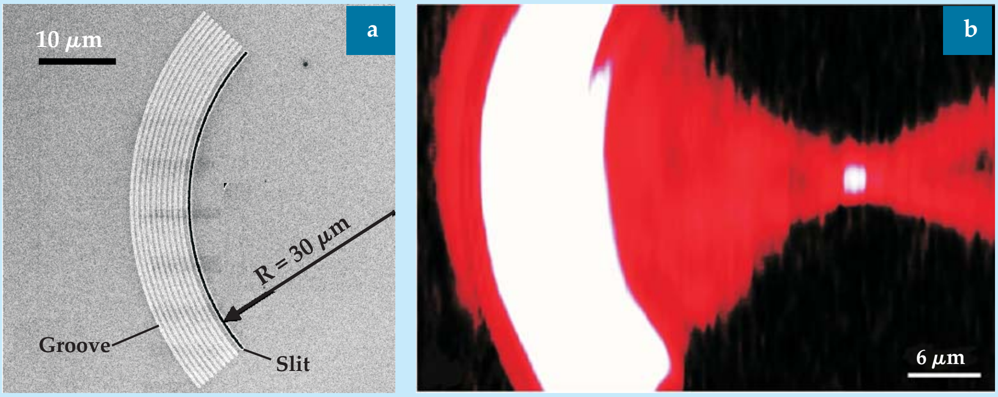


Figure 2. Surface-plasmon launcher. **(a)** The curved slit (400 nm wide), flanked by concentric and periodic grooves (each 200 nm wide), in this scanning electron microscope image acts as a Bragg reflector. **(b)** Laser light at 1520 nm illuminates the back side of the slit, a process that excites SPs on the opposite side of the metal film. Those SPs are then reflected by the grating and focused to a tight spot. The high intensity of light on the periodic reflector is due to decoupling of light into free space. (Adapted from F. López-Tejeira et al., *Nat. Phys.* **3**, 324, 2007.)

alone devices, the ultimate dream is to build a complete, miniature SP circuit that could be engraved, for example, on the surface of an electric wire, with both optical and electrical signals being carried without interference. Optical components—waveguides, switches, Bragg mirrors, couplers, and others—could be incorporated to steer and control SP beams. For more sophisticated signal processing—as in a logical circuit, say—active devices (equivalent to transistors) would be required.

Figure 1 schematically illustrates how such a circuit could be integrated someday on one of the electrical contacts of a chip. It would include various components, of course. But their implementation and design depend primarily on the choice of waveguide, which is not as simple as it might appear.

Waveguiding

Metals have the capacity to support and guide surface waves at their interface with a dielectric medium. To achieve that, the metal must display a negative real part of the (complex) dielectric constant, which is related to the collective motion of the conduction electrons, that is, plasma oscillations. The discontinuity at the metal–dielectric interface induces particular modes of those plasma oscillations—known as surface-plasmon polaritons but often shortened to just surface plasmons—that are distinct from the bulk plasma oscillations by virtue of being coupled to the electromagnetic field outside the metal.

As discussed in box 1, SPs are characterized by both a complex wave vector along the interface, k_{SP}, and one perpendicular to the surface, k_z. The real part of k_{SP} defines the dispersion relation of SPs, and, as expected for evanescent waves, it lies below the dispersion curve of freely propagating light. The deviation between the two dispersion curves increases with the real part of k_{SP}. At the same time, the extension of the evanescent field of the SP becomes more and more confined to the metal. The imaginary part of k_{SP} determines the distance over which the SP can travel along the surface—that is, its propagation length ℓ_{SP}—because it relates to the damping inside the metal. The fact that ℓ_{sp} decreases as the SP becomes more confined reveals an important fact in the context of SP circuitry, namely, that the maximum propagation length and the maximum field confinement lie on opposite ends of the SP dispersion curve. This fundamental feature is inherent in all SP modes: Stronger SP confinement pushes the field closer to the metal, which results in stronger absorption and thereby shorter propagation.

To construct a robust SP circuit, therefore, a compromise between confinement and propagation must be found. The goal is to ensure that the SP wave remains trapped at the surface, even in the presence of defects, while the SP propagation length is greater than the total length of the circuit. At telecommunication wavelengths, around 1.5 μm, ℓ_{SP} can reach values close to 1 mm at the interface of a metal such as silver.[3] Such length is more than sufficient to make a circuit that contains several devices.

To increase the confinement and propagation length, different strategies have been proposed and tested over the years. One of the most interesting approaches uses thin metal strips embedded inside a dielectric to guide the SPs.[4] It has been known since the late 1960s that metal films whose thickness is on the order of the skin depth can sustain so-called long-range SPs (LRSPs).[7] SP modes on both interfaces of the strip overlap through the metal, couple, and form two new modes with opposite symmetry. The mode that is symmetric in the electric-field component perpendicular to the surface has a smaller fraction of its field inside the metal and hence propagates much farther. Simultaneously, the LRSP modes move closer to the light line with decreasing film thickness and strip width and thus become weakly confined, thereby losing the advantage of subwavelength confinement possible with SP modes. Nevertheless, LRSPs have been successfully used to create all kinds of photonic components, from routers and wavelength filters to switches and modulators, with losses of only 1 dB/cm using 10-nm-thick strips at telecommunication wavelengths; box 2 discusses a few examples.

The LRSP structures are, like conventional dielectric ones, diffraction-limited in the sense that the lateral mode confinement is limited by the light's wavelength in a given medium. Furthermore, such low propagation losses can be achieved only for modes that extend laterally over several wavelengths. As a result, significant radiation losses can occur in circuit geometries that contain sharp bends and high curvatures.

One approach for overcoming the diffraction limit uses nanowires surrounded by (the same) dielectric,[8] whose SP modes are somewhat similar to the asymmetric, short-range modes of thin films. Another uses channel plasmon polaritons (CPPs)[9]—SP modes that are trapped at the bottom of grooves engraved in a thick metal film—which strongly confine the SP field. Such groove structures belong to a family of

Box 1. Fundamentals of surface plasmons

Surface plasmons are guided waves at the interface between a metal and a dielectric. These trapped waves are generated because the free electrons of a metal can respond collectively to an electromagnetic disturbance, whether induced by incident light or by incident fast electrons. As a result, SPs have mixed electromagnetic-wave and surface-charge character, as illustrated in the figure below.[3] The field of the SP is evanescent perpendicular to the surface and decays exponentially into the metal on one side and into the dielectric on the other. (The penetration of the field into the metal is much smaller due to the screening effect of the free charges.)

An important consequence of the SP's evanescent nature is the momentum mismatch between incident light and the SPs; that mismatch must be overcome to generate SPs from an incident, propagating light beam. It can be seen in the figure at right as the difference between the dispersion curve of the SP (red) and that of freely propagating light—that is, the light line (gray)—at a given wavelength.

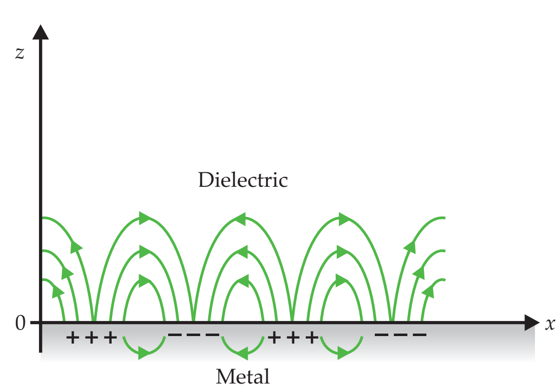
To understand how that evanescent nature matters to SP circuitry, consider the transverse electric field normal to the surface plane inside the dielectric ($z > 0$), E_z^d, and the field inside the metal substrate ($z < 0$), E_z^m:

$$E_z^d = E_0^d \, e^{ik_z^d z} e^{ik_{SP}x}, \qquad (1)$$
$$E_z^m = E_0^m \, e^{-ik_z^m z} e^{ik_{SP}x}.$$

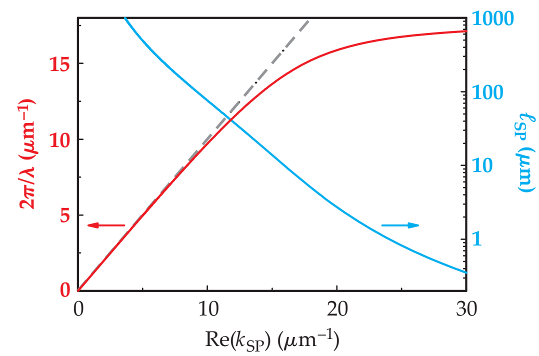
The wave vector of the SP along the interface, k_{SP}, is determined by the dispersion relation

$$k_{SP} = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}, \qquad (2)$$

where ε_d and ε_m are the permittivities of the dielectric and the metal, and λ is the free-space optical wavelength. Because a metal's dielectric constant is complex, so is k_{SP}.



Electric field lines (green) and charge distributions associated with a surface plasmon traveling on a metal–dielectric interface.



Dispersion relation (red) and propagation length (blue) of the surface plasmon on a planar gold–air interface. These plots were obtained by modeling the complex dielectric constant of the metal using a simple Drude model, including dissipation, and equations 2 and 3. The gray dashed line is the light line, light's dispersion relation.

The SP is also characterized by a wave vector k_z, which accounts for its extension normal to the surface on either side of the interface. That complex wave vector, whether describing the field in the dielectric (d) or the metal (m), is determined by $(k_z^{d,m})^2 = \varepsilon_{d,m}(2\pi/\lambda)^2 - (k_{SP})^2$, with the imaginary part of k_z^d greater than zero. The magnitude of the imaginary part of k_z decreases with the real part of k_{SP}. So when k_{SP} decreases and approaches the light line, the SP is less confined and more easily decoupled from the surface into freely propagating light.

The SP propagation length ℓ_{SP}, the distance along the surface that SPs can travel before they attenuate away due to damping of electron oscillations, is a critical parameter for making photonic circuits. It is defined from the imaginary part of k_{SP}:

$$\ell_{SP} = \frac{1}{2\,\mathrm{Im}(k_{SP})} = \frac{2}{[\mathrm{Re}(k_{SP})]^3}\,\frac{[2\pi \mathrm{Re}(\varepsilon_m)]^2}{\lambda^2 \mathrm{Im}(\varepsilon_m)}. \qquad (3)$$

As a function of Re(k_{SP}), the evolution of ℓ_{SP} can be compared to the dispersion curve. As Re(k_{SP}) increases, so does the deviation of the SP dispersion (red) from the light line, and the SP becomes increasingly localized. At the same time, the propagation length (blue) decreases due to resistive damping inside the metal.

Therefore, the maximum propagation length and maximum SP confinement lie on opposite ends of the dispersion curve. The experimental challenge is to find waveguide geometries that can support SPs over long distances with a small mode extension. At telecommunication wavelengths, two designs are quite promising: long-range SPs and channel plasmon polaritons, described in box 2.

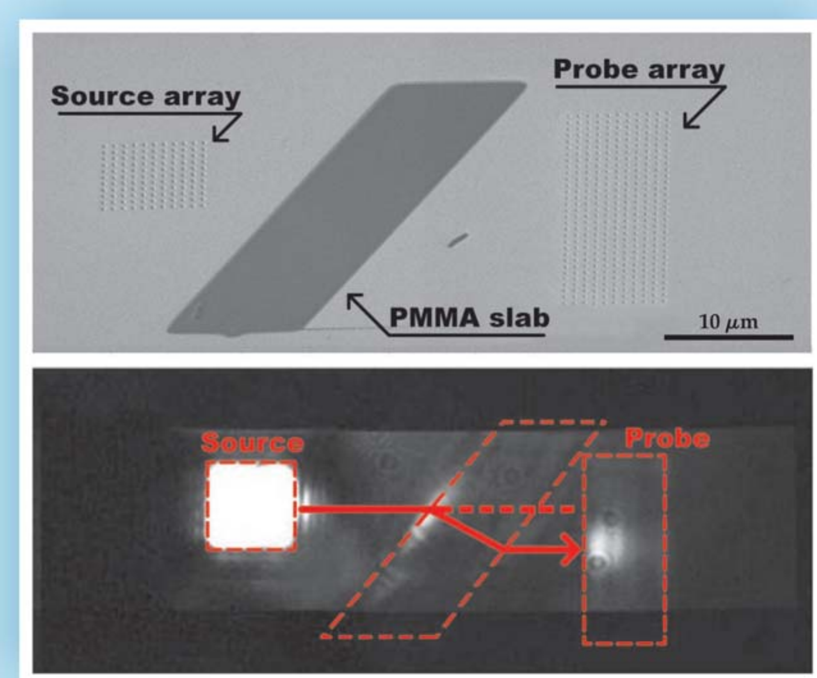


Figure 3. Surface-plasmon refractor. After an SP beam has been launched by the diffraction of light from the back side of a subwavelength array of holes (left) in a gold film, it crosses a dielectric (polymethyl methacrylate, PMMA) parallel plate before reaching a second hole array, which scatters the beam into free space. The far-field image at bottom reveals the generation of freely propagating light as the SP beam enters the parallel plate. This occurs because evanescent SP waves enter a dielectric medium with a higher refractive index, which facilitates the decoupling of light from SPs on the surface. (Courtesy of Jean-Yves Laluet; for other examples of refractive elements, see A. Hohenau et al., *Opt. Lett.* **30**, 893, 2005.)

waveguides whose modes are supported by a narrow gap between two metal surfaces, in contrast to the modes of thin metal films discussed above. In gap waveguides,[10] the SP modes on opposite walls of the gap overlap, couple, and form two new modes with opposite symmetry. However, the only mode that survives for all gap widths—the so-called gap SP or GSP—is the one whose normal (transverse) electric-field component maintains its sign across the gap.

The effective refractive index—the index averaged over the metal and the dielectric medium into which the SP field extends—dramatically increases as the gap width decreases below the SP wavelength in the circuit. Simultaneously, the GSP propagation length decreases as well, though not as drastically as other SP modes. GSPs with their better confinement can even exhibit longer propagation. That remarkable effect is a consequence of the field distribution rapidly becoming nearly constant across the gap. The field thus fills the gap space most efficiently, minimizing the losses that would otherwise occur in the metal.

In the case of CPPs, the field is mainly confined to the bottom of the groove where the effective index is at its maximum. Consequently, the CPP waveguides provide a path to robust circuits whose SPs are well confined yet still propagate through the circuit without losing much signal strength. Miniature devices can be constructed from bent CPP waveguides having radii of curvature comparable to the SP wavelength.

Coupling

The waveguiding capacity of a metal surface is intrinsically related to the evanescent character of SPs. Such character guarantees the robustness of the waveguide but paradoxically makes launching SPs and decoupling them from the surface into freely propagating light more challenging. The dispersion curves pictured in box 1 show that the coupling and decoupling processes must provide the momentum difference between the light and SPs. There are several ways to do that, depending on the chosen waveguide configuration.

One attractive option for optoelectronic circuits is to generate SPs by having electrons tunnel across either a metal-insulator-metal or a semiconductor-insulator-metal junction. The challenge here is to overcome the low efficiency of the process. Therefore, SPs are generally launched by coupling incident light directly into the waveguide.

Two general schemes are used to couple light to the SPs. In the first, the coupling is achieved by matching their momenta. According to the dispersion relation in box 1, the parallel component of a spatial wave vector must be added to the incident light beam so that it matches the SP wave vector. That can be done simply with a prism covered with an optically thin metal film. When an incident light beam impinges on the metal film from the glass side, SPs can be launched on the metal–air interface by evanescent coupling through the film. Another way to provide the additional wave vector is to incorporate a structure with the right components in its spatial Fourier spectrum. For instance, surface structures smaller than the incident wavelength, such as a narrow slit, allow natural coupling to evanescent waves and, therefore, are often used to launch SPs in a circuit. Figure 2 shows an example of a diffraction slit that acts as such a coupler. Gratings such as arrays of holes, dimples, and nanoparticles are also used to launch SP beams.

In a different approach, the coupling doesn't rely on matching wave-vector components parallel to the surface but instead relies on matching field distributions across the end face of a metal–dielectric interface. That is known as end-fire coupling and is particularly suitable for launching SPs into waveguides discussed earlier.[11] The method is efficient and, more importantly in the context of circuitry, allows a large range of frequencies that can be coupled for a given geometry. Ultimately, this broadband capacity will be a critical issue for a practical circuit.

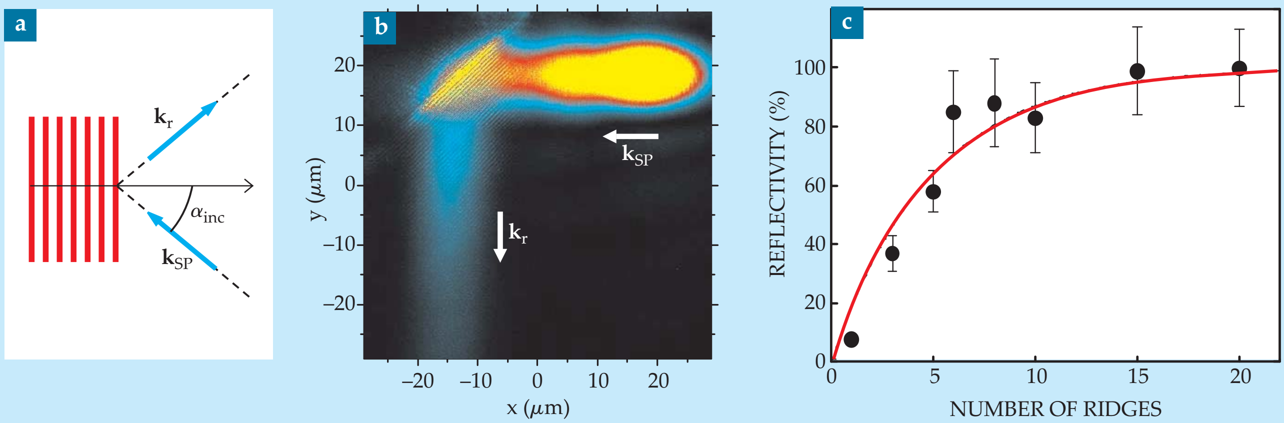


Figure 4. (a) A Bragg mirror, a set of parallel ridges etched into a metal surface, reflects an incident surface plasmon of wave vector $\mathbf{k}_{SP}$ at an angle α_{inc} to an outgoing SP of wave vector $\mathbf{k}_r$. **(b)** This near-field image shows the reflection of an 800-nm-wavelength SP beam on a Bragg mirror composed of 20 ridges (75 nm high, 190 nm wide) on a gold film. **(c)** The mirror's reflectivity can be adjusted by changing the number of ridges in the reflector. (Adapted from M. U. González et al., *Phys. Rev. B* **73**, 155416, 2006.)

At the end of a circuit, the SP signal can be converted to an electrical signal via a photodetector in the metal plane or can be decoupled into freely propagating light. The latter process is the reverse of the coupling process just described, as any defect or grating structure can efficiently scatter the surface wave into free space. However, the real challenge lies in producing a free-space beam that can, in turn, be used and recovered at a distance by another optical circuit or detector. Much work remains to conceive and test decoupling structures that are specially tailored to provide a well-defined beam profile, which would make them viable in a real circuit.

Passive and active devices

A number of passive and active devices are obviously necessary to control the SP beam and process a signal in a circuit. Much of the research effort has concentrated on two-dimensional passive elements such as lenses, prisms, and beamsplitters. Making such elements can be more complex than one might think. Consider the example of a refractive element such as a parallel plate in the path of an SP beam as pictured in figure 3. The far-field image reveals that a significant fraction of the SP beam decouples as it enters the dielectric plate. The decoupling is facilitated by the sudden change in refractive index. One of the challenges in building a practical SP circuit is finding ways to minimize such losses.

A reflector is a key component to steer an SP beam. For that purpose, Bragg reflectors or mirrors, composed of a succession of scattering planes, have been widely studied both theoretically and experimentally. Figure 4 illustrates an example. The best results are obtained using rows of ridges, which, when optimized, can reflect nearly 100% of the incoming power.

One way to make various ultracompact photonic components is to use CPP waveguides, which can strongly confine the SP beam and yet keep propagation losses to acceptable levels. Consider as an example the simple add–drop multiplexer: The CPP-based ring resonator pictured in box 2 has recently been shown to work at telecom wavelengths, suffers an insertion loss of less than 3 dB, and occupies a footprint of just 100 μm^2 in a circuit. Two straight waveguides couple the input and output radiation to CPP modes and exchange power via a 5-μm-radius ring waveguide inserted between them. Depending on the phase accumulated by the CPP traveling around the ring, which is determined by the CPP wavelength and ring circumference, the input radiation, end-fired with a tapered optical fiber, appears at the through or drop port of the multiplexer.

To be complete, an SP circuit will require active devices that can modulate the beam and give rise to logic functions. Several options are available, such as electro-optical, thermo-optical, and all-optical devices. LRSP-based thermo-optical modulators and switches were the first plasmonic components in which the same metal circuitry was used to both

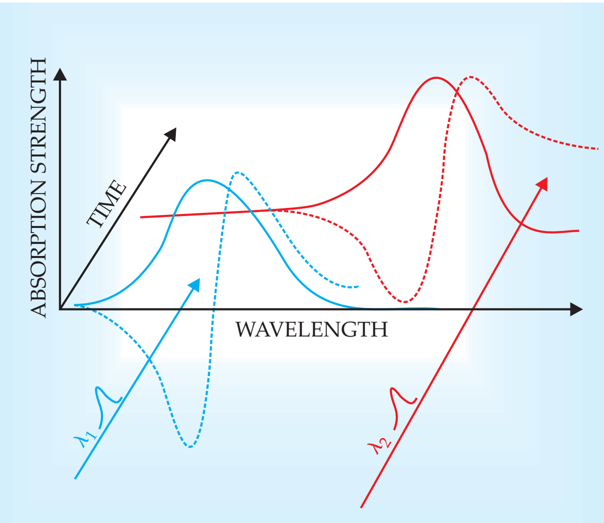


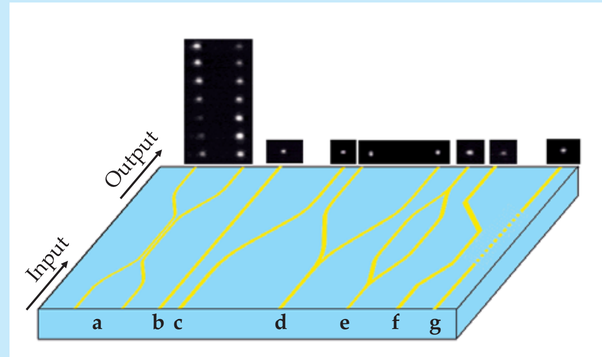
Figure 5. All-optical index modulator. Light of wavelength λ_1 incident on a material can change its absorption band from the blue to the red, thereby inducing a corresponding variation in the refractive index (dashed lines) around the absorption band (solid lines). That variation in the refractive index can then be used to modulate the propagation of a light beam through the material at λ_2. (For further details, see T. W. Ebbesen, *New J. Chem.* **15**, 191, 1991.)

Box 2. Surface-plasmon waveguides

A variety of surface-plasmon waveguide geometries and devices have been tested over the years. When considering the compromise between propagation length and field confinement, discussed in box 1 and in the main text, SPs on very thin metal strips (so-called long-range SPs or LRSPs) and those traveling at the bottom of V-shaped grooves (so-called channel plasmon polaritons or CPPs) appear to be most promising. Below are some examples of structures and devices that have been fabricated using those two types of SPs.

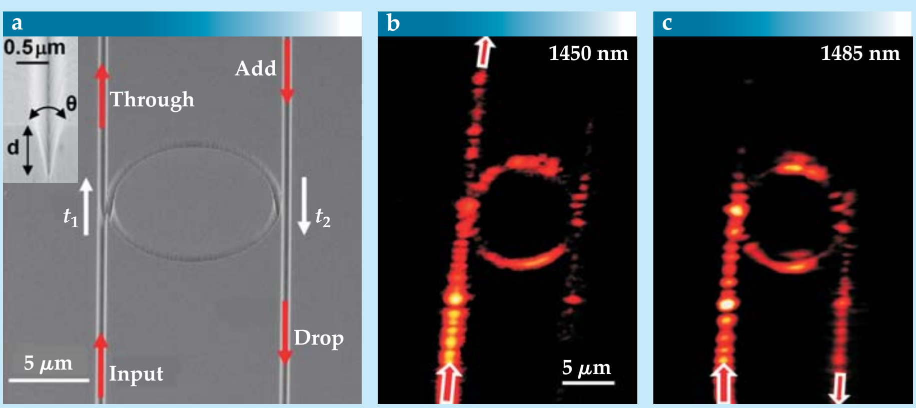
The figure at right illustrates various passive LRSP waveguide structures fashioned out of thin gold strips, each embedded in a silicon dioxide cladding. Experimental spots of light are shown at the output of each waveguide and were recorded in the far field for each strip; the strips are 20 nm thick by 8 μm wide.

A comparison of the spots recorded in **(a)** reveal how even slight variations in the spacing between parallel strips change the coupling between them. The other waveguides illustrate, from **(b)** to **(g)**, the output of a straight 3.5-mm-long waveguide, an S-bend, a beam splitter, a Mach–Zehnder interferometer, sharp angle bends, and a Bragg grating made up of closely spaced gold islands. (Image adapted from P. Berini, *Phys. Rev. B* **61**, 10484, 2000, and R. Charbonneau et al., *Opt. Express* **13**, 977, 2005.)



Although CPPs propagate over shorter distances than LRSPs, they provide better confinement. This feature allows for structural designs with sharper turns (for example, curvature on the order of the wavelength); therefore much more compact devices and circuits can be fabricated. Below, the scanning electron microscope image **(a)** presents the example of an add–drop multiplexer, which filters the input of one data stream and channels the output into different directions depending on the input wavelength. The inset image shows the shape of the groove cut into the gold layer.

The optical near-field images **(b, c)** reveal that two different wavelengths exit into different arms of the waveguide. The suppression of the dropped wavelength in the through channel demonstrates efficient wavelength filtering with a bandwidth of about 40 nm. In principle, radiation at the dropped wavelength can also be added into the through port by end-firing the add port. (Images adapted from S. I. Bozhevolnyi et al., *Nature* **440**, 508, 2006, and V. S. Volkov et al., *Nano Lett.* **7**, 880, 2007.)



guide the optical radiation and transmit the electrical signals that control the guidance.[12] Thin gold strips embedded in polymer are heated by electrical currents. That heating changes the effective refractive index of the LRSP modes that are supported by the strips. Using well-known schemes, interferometric modulators (devices that modulate the transmission intensity by playing on the interference between different optical paths) and directional-coupler switches (devices in which mode coupling between parallel waveguides is controlled by their relative phase) have been built. The devices operate at telecommunication wavelengths, require low power (about 10 mW), and produce high extinction ratios—the relative ratio of output to input power—with moderate response times.

All-optical control would provide the fastest and the highest integration capacity. Although such all-optical devices have not yet been implemented in actual circuits, standalone devices have tested the principles that could possibly be used to integrate devices in the future. Researchers have demonstrated, for instance, the feasibility of optically bistable media[13,14] and molecular[15] or nanoparticle[16] resonances. The latter schemes are essentially transistor switches that can be operated at the quantum level.[17] The basic principle behind such devices is that different states of molecules or nanoparticles exhibit distinct absorption spectra. The change in a molecule's absorption by a control beam—whether optical or SP—changes the refractive index of the medium and allows, therefore, the switching or modulation of a second, SP beam (see figure 5).

Future prospects

It should be clear from what has been presented above that a large number of elements necessary for a full SP miniature circuit have been realized, although much work is still needed. Because of the complexity of the tasks, various parallel paths and options are being explored and compared. Out of the diversity, the most promising possibilities will naturally emerge for further development. The interplay between theoretical and experimental work has been very important in the progress made so far. The electronic analogy for circuit design is certainly worthy, but one must keep in mind that in SP circuits the near-field characteristics are intimately linked to the properties of any device, especially in the subwavelength regime. Therefore, computations that provide information in that regard are precious guides for designing devices.

As researchers are moving toward the implementation of SP-device networks, one pressing issue is the temporal characterization of those devices using pulsed signals. Those tests will certainly help in discriminating between various options regarding rate performance. One interesting perspective in telecommunications is to slow pulsed signals in order to help in synchronizing router conversions by "buffering" packets of information. In that context, a recent study has demonstrated that guided SP femtosecond wavepackets can be slowed down by a factor of 2, at telecom wavelength, using a plasmonic Bragg grating designed with a gold guiding strip.[18]

In addition to the work targeting circuits, there has been considerable research activity on standalone devices that take advantage of SP properties (such as high fields and strong confinement) for a variety of applications. These include filters, sensors, switches, photovoltaics, emitters, and photodetectors. For instance, in the last case, ultrafast silicon photodetectors have been created by using metal structures as antennas to couple light to SPs. Mounted directly on chips, they could help provide precise clocking between chips and improve the optoelectronic integration.

Ultimately, practical photonic circuits might use a combination of plasmonic and dielectric components, taking advantage of the best performance available. In other words, whether the outcome will lead to pure or hybrid SP circuits, the activity stimulated by plasmonics will bring the much older dream of an integrated optical circuit ever closer to reality.

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