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Plasmonic circuits for manipulating optical information

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Abstract: Surface plasmons excited by light in metal structures provide a means for manipulating optical energy at the nanoscale. Plasmons are associated with the collective oscillations of conduction electrons in metals and play a role intermediate between photonics and electronics. As such, plasmonic devices have been created that mimic photonic waveguides as well as electrical circuits operating at optical frequencies. We review the plasmon technologies and circuits proposed, modeled, and demonstrated over the past decade that have potential applications in optical computing and optical information processing.

Keywords: nanorods; optical computing; optical devices; optical logic devices; optical properties of nanostructures; optical signal processing; plasmonics.

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1 Introduction

Optical information processing (optical computing) has been an active topic of research for at least six decades already [1]. In its original form, Fourier transforms of coherent light distributions were performed using lenses, enabling extremely fast and highly parallel data processing such as correlations for object recognition. There has been renewed interest in all-optical methods to process signals in communication networks [2, 3] with the idea of using optical processing elements to enable "software-defined networks" [4, 5] necessary to simplify network reconfigurability. As data in optical communications can be encoded using amplitude, phase, intensity, wavelength, and polarization, direct serial operations between light signals can eliminate the complex optics-electronics-optics conversion, thereby maintaining the encoding during processing.

However, there are good reasons electronics is used for computation whereas optics is used for communication [6]. Electronics is based on the movement of electrons, with signals encoded using current or voltage. The operation frequency of electrical circuits is limited by the rate at which electrons can move, which in turn is governed by inductive and capacitive effects as well as resistive losses associated with electron propagation in materials. Electronic systems are capable of strong non-linear behaviors, such as switching and state changes, because of the strong interaction between electrons mediated by their electric fields. More fundamentally, electrons have mass and therefore can be confined in stationary states in small regions of space, which is important for memory. Electronic circuits are characterized by electron propagation through wires, resistance, capacitance, inductance, and non-linear behavior as represented by transistors (Figure 1).

Photonics is based on the propagation of light. Unlike electrons, the optical signal can be encoded directly on the photon wave function, such as by modulating the polarization or the phase of the beam, which takes advantage of the coherent nature of the wave. The carrier frequency of an optical electromagnetic wave is exceptionally high, in the region of hundreds of terahertz, enabling very large data transfer rates. However, photons interact very weakly with one another, if at all, so that all-optical modulation and switching are difficult to achieve [7]. With very intense beams, it is possible to drive non-linear changes in material properties, such as refractive index changes, that can be used for modulation or by using electro-optical effects whereby an electrical signal changes the optical properties of a material to modulate the light beam. Currently, information in communications networks is processed by converting the optical signal into an electronic one and

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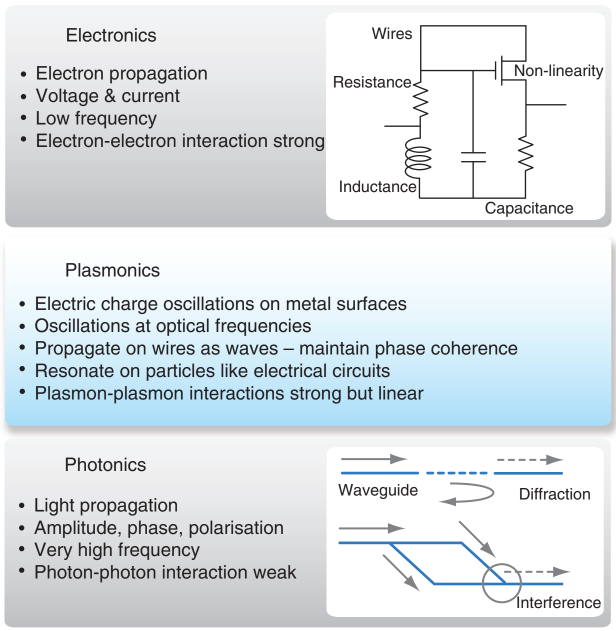

Figure 1: A comparison between electronic and photonic circuits. The field of plasmonics lies in between.

then applying electronic signal processing methods. This is not a coherent process, and the phase information associated with the light beam must be decoded and converted into an electrical signal. Moreover, photons have no mass and therefore cannot remain stationary in space, which is problematic for optical memory. Photonic circuits are characterized by waveguides and linear effects such as interference, diffraction, and resonance.

Intermediate between electronics and photonics lies plasmonics. Surface plasmon polaritons (SPPs), often abbreviated to plasmons, are collective oscillations of the conduction electrons driven by light at the surfaces of metals [8, 9]. As such, the plasmons oscillate at optical frequencies, around hundreds of terahertz, and are associated with strong electric fields. The plasmons maintain the phase relationships with the incident light and are therefore coherent excitations. As plasmons can be confined to regions 100 times smaller than light focused to a diffraction-limited spot [10], they provide a means to manipulate optical energy at the nanoscale. This size regime lies in between that of photonics, where device feature sizes are typically above 1000 nm, and that of electronics, for which transistor feature sizes are now approaching 10 nm. Plasmons propagating on metal structures such as plane surfaces, grooves, or wires or even confined to small metal particles [where they are known as localized surface plasmons (LSPs)] have been described as light on a wire [11].

It is fair to say that very little has been done using plasmonics for optical computing or optical information processing. To date, most of the effort has been directed to understanding the basic principles and demonstrating devices in proof-of-principle experiments. The resurgence in the study of surface plasmons has been driven by the optics community, and as such, most applications of plasmonics mimic configurations in optics or photonics, such as waveguides, devices for converting polarization, optical filters, and so on [12]. However, plasmons represent the extreme frequency limit of the classical skin effect well known in radio frequency engineering, which has led to descriptions of plasmons in terms of electric circuits, antennas, and electrical filters.

In this review, we examine the optical and electrical circuit descriptions of plasmonics and then present some recent ideas on plasmonic systems that may have applications in optical-domain information processing.

2 A brief overview of surface plasmons

Research into SPPs has burgeoned in the last 16 years, driven largely by the emergence of methods for nanoscale structuring of metals [13–20]. Although strictly a quantum quasi-particle composed of coherent charge oscillations, plasmons can be described classically using Maxwell's equations of electromagnetism, which predicts the presence of propagating electromagnetic waves trapped at the interface between a dielectric and a metal (Figure 2). These are SPPs. They are the combined effect of the electron plasma at the metal surface coupled to the polarization charges induced in the dielectric. Light with a free-space wavenumber $k_0=\omega/c$ will create surface plasmons with a wavenumber $k_{\mathrm{spp}}=k_0\sqrt{\epsilon_m\epsilon_d/(\epsilon_m+\epsilon_d)}$, which depends on the relative electric permittivity of the metal $\epsilon_m(\omega)$ and that of the adjacent dielectric ϵ_d. At optical frequencies, $\epsilon_m<0$ is negative and large $|\epsilon_m|\gg\epsilon_d$ so that $k_{\mathrm{spp}}>k_0\sqrt{\epsilon_d}$. This means that the plasmon wavelength is smaller than that of the light and the plasmon is unable to radiate into the dielectric, becoming trapped at the surface (Figure 2A and B). Furthermore, it is then quite difficult to excite surface plasmons as light from the dielectric cannot be phase-matched to it. However, plasmons radiate at discontinuities such as ridges or pits in the surface or abrupt changes in the dielectric, and likewise, light incident on these discontinuities can excite surface plasmons (Figure 2C). These discontinuities can also reflect and scatter plasmons [20, 21].

A thick metal film with dielectric materials adjacent to both surfaces will support two independent plasmon

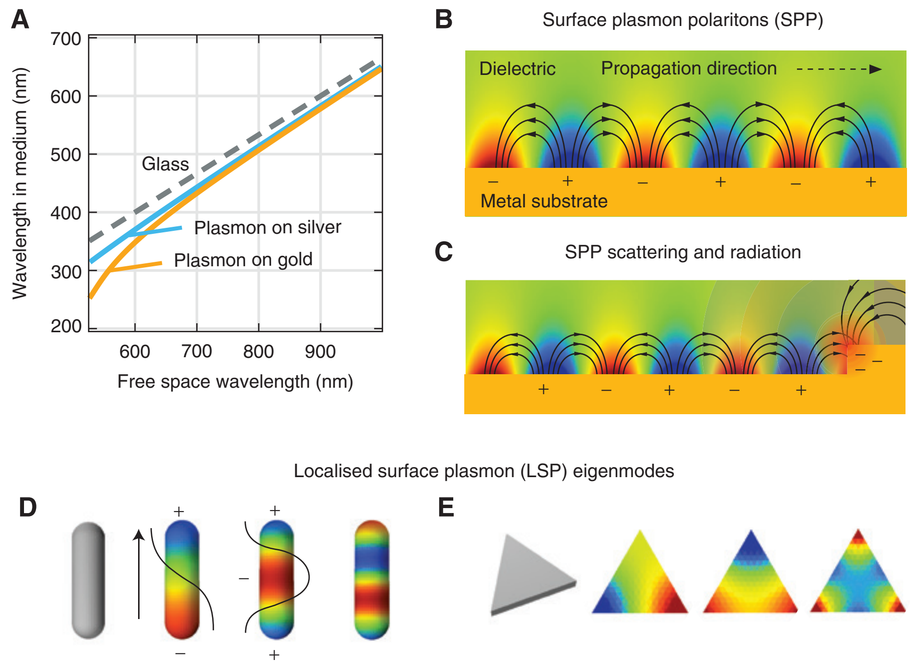

Figure 2: Plasmons propagating on surfaces: (A) The wavelength of an SPP is shorter than the free space wavelength of light or the wavelength within the dielectric, which prevents the plasmon from radiating; (B) the electric field associated with an SPP propagating over the surface of a thick metal film; (C) illustration of a plasmon scattering at a discontinuity with some energy converted to radiation in the dielectric; (D–E) examples of LSPs on different metal particles. These show the charge distributions (blue positive, red negative) of different resonant modes. The fundamental mode is a half wavelength with a strong dipole moment.

waves, one for each surface, with wavelengths depending on the permittivities of the dielectrics. If the metal film becomes thinner than the skin depth of the electromagnetic wave, the plasmon electric fields penetrate the full thickness of the film leading to coupled modes and mode splitting [22]. For such thin films, it is possible to excite surface plasmons using special geometries (Kretschmann, Otto) and appropriately chosen dielectrics [8, 9].

As plasmons propagate as waves, they can reflect, scatter, diffract, and interfere, which enables them to be used in much the same way that light is used in photonics. At certain frequencies, plasmons excited on the surfaces of metal particles exist as standing waves (Figure 2D and E), which are known as LSPs. The characteristic frequencies correspond to LSP resonances [23] and are associated with a large number of possible standing wave modes [24]. As these particles are generally much smaller than the wavelength of light, with dimensions typically between 10 nm and 200 nm, no phase-matching condition is necessary and LSPs can be excited simply by shining light on the particles at an appropriate frequency, but only those modes that have non-zero electric dipole moment are excited, the other modes, appearing “dark”. Because of losses in the metal (essentially Ohmic losses), the resonances are much broader than those usually found in spectroscopy on atoms and molecules, with quality factors around $Q\sim10$ (for example, see Figure 6A). Metals such as aluminum, gold, and silver are commonly used in plasmonics because of their relatively low loss at optical frequencies.

In the following sections, we will discuss different devices created using surface plasmons. Most of these devices have been used for proof-of-principle demonstrations and may not be practical in real applications. We begin by examining research into devices based on plasmon waveguides that use the wave-like properties of plasmons propagating over surfaces or within special guides to demonstrate both linear and non-linear optical devices for manipulating light at the nanoscale. As plasmon emission and detection is important, we briefly present some research into plasmon emitters and detectors as well as coupling to fluorescent materials. We then examine plasmonics from the point of view of electronics and review research on LSPs that mimic inductor-capacitor circuits operating at optical frequencies. Within this topic, we consider optical antennas, optical circuits, and concepts for performing mathematical operations on light fields. A brief mention of quantum plasmonics follows. Finally, because of the losses encountered with metals, there has been work towards low loss materials supporting surface plasmon propagation.

3 Plasmonic waveguide circuits

Surface plasmons can propagate as waves over metal surfaces, and because plasmon wavelengths can be much smaller than light at the same frequency, they have potential in highly compact optical devices. The optical properties of these waves on surfaces have been studied [20] and applied to simple optical elements. For example, it was shown that a converging lens for surface plasmons can be created by slits cut into the metal film, which performs an optical Fourier transform analogously to macroscopic lenses, enabling traditional optical computing on-chip [25]. One of the issues with "free" plasmon propagation over surfaces is creating the plasmon in the first place. One solution is to etch a slot through the metal film to the transparent substrate. When the slot is illuminated through the substrate, the electric field penetrates to the top surface, launching plasmon waves that propagate in either direction away from the normal to the slot edge. By including slot reflectors in the surface, it is possible to interfere the plasmon waves enabling devices such as binary encoders [26], logic discriminators [27], and multiplexers [28]. Similarly, arrays of holes can be used to launch plasmons and to convert the energy back into freely propagating light [29].

Plasmon waves can be confined and guided by a thin metal strip. The motivation for such work is based on the idea that light can form high-speed and low-loss interconnects for electronic circuits and the use of plasmons enables very compact devices, an order of magnitude or smaller than the wavelength of light [14, 15, 17, 30–32]. Similar to light travelling in optical waveguides, the plasmons propagate with one or more different modes on the metal strip, depending on the strip geometry and the electric permittivities of the metal and the surrounding medium. A systematic study of the propagation in these guides [33–35] demonstrated the existence of a short-range and a long-range mode. The short-range mode is lossy because there is strong penetration of the plasmon electric field into the metal, creating electrical currents that lose energy by Ohmic resistance. The long-range mode has the plasmon electric field predominantly in the dielectric region about the waveguide, thereby reducing losses. Transmission of optical signals by plasmons in strip waveguides has been demonstrated at telecom wavelengths with data rates of 10 Gbs [36]. There have also been investigations of plasmon propagation in more complicated multi-layer guides [22, 37] as well as arrays of particles [38–41].

As loss is a big problem with plasmon propagation in metals, there have been many studies looking for configurations of metals and dielectrics that minimize the penetration of the electric field into the metal [18]. These include grooves, slots, metal-insulator-metal designs, and so on (see Figure 3 with typical parameters in Table 1). Important factors in plasmon waveguides are the propagation distance, operating wavelength, and mode area. The propagation distance is limited by absorption, which is problematic in complex plasmonic circuits. The mode area describes the cross sectional area of the region containing the optical energy. Large mode areas reduce the ability to create compact devices. For example, subwavelength plasmon-polariton guiding by triangular metal wedges has been demonstrated [42] with propagation lengths ~ 120 μm and mode widths ~ 3 μm. Other proposed strategies to mitigate Ohmic losses in plasmon oscillation and propagation include the interaction of plasmons with gain media [43–47].

Metal-insulator-metal (MIM), sometimes referred to as metal-dielectric-metal (MDM), and gap plasmon polariton (GPP) waveguides have the advantage of simple

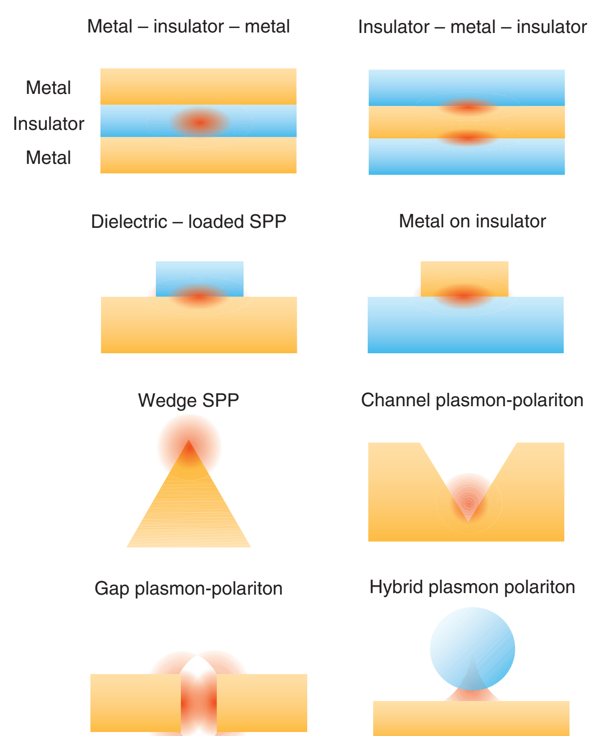

Figure 3: Cross sections of different types of plasmon waveguides (adapted from Ref. [18]).

Table 1: Comparison of plasmon waveguide optical confinement (mode area), propagation length L and free space wavelength λ (from Ref. [18]).

Waveguide type	Mode width/λ	Mode height/λ	Mode area/$(\lambda/2)^2$	L/λ	λ (nm)
GPP	0.13	0.13	7%	13	1550
Wedge	~0.47	N.A.	N.A.	2	633
MIM	0.5	0.2	10%	5	685
IMI	0.19	~0.19	~14%	14	1550
V-groove	0.65	>0.84	>200%	~52	1550
DL-SPP	0.62	N.A.	N.A.	10	800
DL-SPP	N.A.	N.A.	3%	4	1550
	0.04	0.04	0.6%	21	1550
	0.14	0.04	2%	N.A.	1427
HPP	0.31	0.06	7%	21	808
	0.09	0.08	3%	11	633
	0.15_{theory}	0.05_{theory}	3%	24	1310

N.A., not available.

fabrication in that they can be constructed by cutting a slot in a metal film and filling the slot with a dielectric [31, 48]. Likewise, dielectric loaded plasmon waveguides only require patterning of a dielectric layer on top of a metal film, which can be done directly using lithographic resist such as PMMA. Guiding in "V"-shaped grooves in metals has been demonstrated along with typical waveguide elements [17, 30] such as splitters and ring resonators. A theoretical analysis of plasmons in channels showed that increasing wavelength caused the fundamental mode to shift from the bottom of the channel and become more like wedge plasmons, being guided by the upper edges [49]. The plasmons guided by wedges at telecom wavelengths are better confined (smaller mode area) without increasing loss [50].

The choice of one waveguide geometry over another depends on the application. If long propagation distance is required, then one might choose a V-groove or hybrid plasmon-polariton geometry, or if small mode area is necessary, then an insulator-metal-insulator design may be preferred. However, these waveguides may not be compatible with the overall microfabrication process, in which case some trade-off will be required.

3.1 Emitters and detectors for integrated plasmonics

With the development of plasmon waveguide devices, there has been some research into methods of launching plasmons directly on-chip. Most of these works have been proof-of-principle demonstrations of devices with potential for integration in plasmonic circuits, but they are significantly less advanced than corresponding devices used in photonics. In one example, a nanoscale light emitting diode with a subwavelength footprint directed some of its emission into a single-mode slot plasmon waveguide [51]. Additionally, the prospect of stimulated emission of plasmon radiation has been studied [19, 43, 52] and a device was fabricated and demonstrated [53]. This nanoscale plasmon emitter was constructed from 44-nm-sized nanoparticles with a gold core and a dye-doped silica shell. Surface plasmon oscillations were outcoupled to photonic modes at a wavelength of 531 nm. At the quantum limit, there have been experimental demonstrations of the excitation of surface plasmons by single photon emitters. Importantly, these experiments reveal that the radiative decay of a plasmon excited by a single photon also yields a single photon, even though a surface plasmon is a collective phenomenon consisting of the in-phase oscillations of a large number of electrons [54–58].

Active plasmonic devices including those with gain have been reviewed elsewhere [59]. Gain media consist of materials with electronic states that can be optically excited and subsequently de-excited in phase by another light beam, as occurs in solid-state lasers. Plasmon gain requires the gain media to emit in phase with the propagating plasmon. Amplified spontaneous emission from a polymer waveguide film containing laser dye molecules excited by surface plasmons and pumped by another laser has been observed [60], and there has been a demonstration of plasmonic propagation with net positive gain provided by an optically pumped layer of fluorescent polymer in a dielectric-metal-dielectric waveguide [61]. Incoherent plasmonic gain has been predicted with three-level fluorescent semiconductor nanocrystals in the presence of another semiconductor with negative electric permittivity

[62]. Spontaneous emission from nanosized particles and plasmon resonators has been studied theoretically [63].

Plasmon detectors have also been integrated into devices, such as a Schottky contact device with an asymmetric metal stripe waveguide [64]. Superconducting plasmon detectors were used to detect single plasmon quanta in a quantum interference experiment [65]. Plasmonic components have been used in detectors to alter the responsivity in the mid-infrared [66] as well as in the visible region [67]. In principle, such detectors can be as sensitive as those used in photonics, which is determined largely by the quality of the semiconductor photo-diode fabrication process.

3.2 Linear devices for optical computing

Linear devices based on waveguides tend to mimic those used in photonics. Linear devices use plasmon wave properties such as constructive and destructive interference to perform addition and subtraction operations, respectively. Moreover, plasmon excitation relies on the correct alignment of the incident electric field with respect to the ridges or grooves that launch the plasmons, as the field is required to induce a surface charge. In other words, such launching methods are sensitive to the incident polarization, which provides a means for polarization sensitivity.

Examples of photonic devices created for plasmons are shown in Figure 4 and include “Y” junctions for combining or separating plasmons [68–72], “X” junctions [70], proximity couplers [73], directional couplers [74], Mach-Zehnder interferometers for interfering plasmons [73, 75–78], Bragg grating filters [69, 79], add-drop filters [80], and ring resonators [69, 79, 81] that transmit or reflect plasmon waves depending on frequency and switching using phase shifts [82]. A novel plasmon filter was created using two wires of different materials joined together that provided a large electric permittivity mismatch resulting in unidirectional propagation [83].

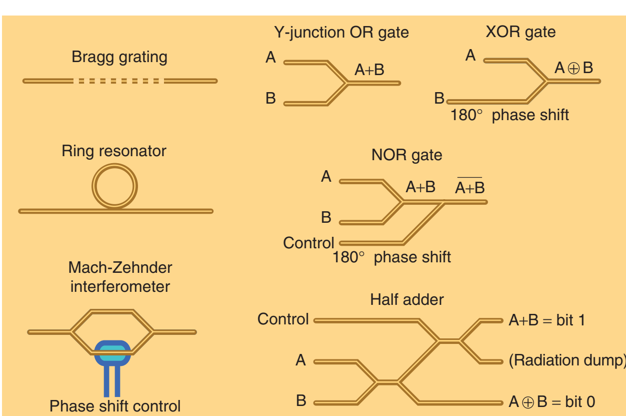

Figure 4: Plasmonic waveguide devices for performing optical processing. The logic circuits operate using phase shifts and interference.

Additive logic operations have been proposed and modeled with such circuits or their variants [84–90]. There have been demonstrations of logic functions such as a NOR gate built from OR and NOT gates [91]; XNOT, XOR, and NOT gates using an air slot etched in gold on silicon dioxide [92] and an XOR gate [93]; an OR gate [94]; a logic comparator [95]; NOT, AND, OR, XOR [96]; a half-adder [97]; demultiplexers [28]; binary encoders [26, 98]; and discriminators [27]. The operations of these gates depend on phase shifts or on frequency (wavelength) differences, which presuppose specific encoding schemes for the digital information. These devices have been used to demonstrate logic operations, but there has been no concerted attempt at fulfilling the requirements of logical optical processes as required in communications networks or optical computing.

More complex arrangements are possible leading to coupling between waveguide modes [22]. Such coupling can be used to create highly compact waveguide interferometers, such as the Mach-Zehnder [77, 78, 99]. As interferometers are very sensitive to phase shifts, they have applications where non-linear effects can be used to modulate the plasmon phase.

3.3 Non-linear devices for optical computing

Linear devices have limited use in many photonic circuits, as they cannot demonstrate bistability or static behavior but require a continuous propagation of plasmon waves to operate (such as required for interference). While plasmon-plasmon interactions and plasmon-material interactions are generally linear, the plasmons have electric field strengths one or more orders of magnitude larger than the light wave electric fields that excite them, which makes it easier to induce non-linear behaviors in materials, enhancing modulation [100]. The non-linearities generally change the local electric permittivity that shifts the phase of propagating plasmons. When combined with plasmon interferometers, these can be quite effective modulators. In addition, it is possible to use electrical signals to induce material changes, particularly in semiconductors where the electron density, and therefore the “metallic” properties, can be altered. These are termed “active plasmonic” devices [101]. The methods for non-linear modulation of plasmons are summarized in Figure 5.

There have been many devices proposed and simulated, such as modulation based on an external electrical signal interacting with graphene to create NOR/AND, NAND/OR, XNOR/XOR gates [102]; third-order non-linear optical materials in which the electric field intensity $|E|^2$ of the plasmon induces refractive index changes, also known as Kerr-nonlinearity [103–107]; intense optical pulses to induce refractive index changes in GaAsInP [108]; polarization sensitive four-wave mixing non-linearity coupled to a plasmon ring resonator [109, 110]; metal-dielectric cavities filled with non-linear materials to create bistability [111] or switching [112]; a three-level system showing gain [62]; beam steering by modulating refractive index [113, 114]; electro-active materials to shift refractive index [115, 116]; and change in resonance by changing refractive index [117] or by changing material properties by electron excitation pumped by light [118, 119] (changes absorption properties within a waveband). One novel device modulated a plasmon wave on a diffraction grating by changing the refractive index of a surface layer of fluid [120].

It is one thing to propose a device but much more difficult to fabricate and demonstrate one. Plasmonic devices based on non-linear effects can be classified into several different categories: those where the plasmon does the modulation, those where an external light signal does the modulation, and those where an external electrical signal does the modulation. These methods are summarized in Figure 5.

3.3.1 Direct plasmon modulation

Surprisingly, there have been few experiments demonstrating plasmon-plasmon modulation. As the plasmon is associated with a strong electric field, a propagating plasmon wave can directly induce enough refractive index change in a material to affect the phase of another plasmon. Nevertheless, the Kerr non-linearity

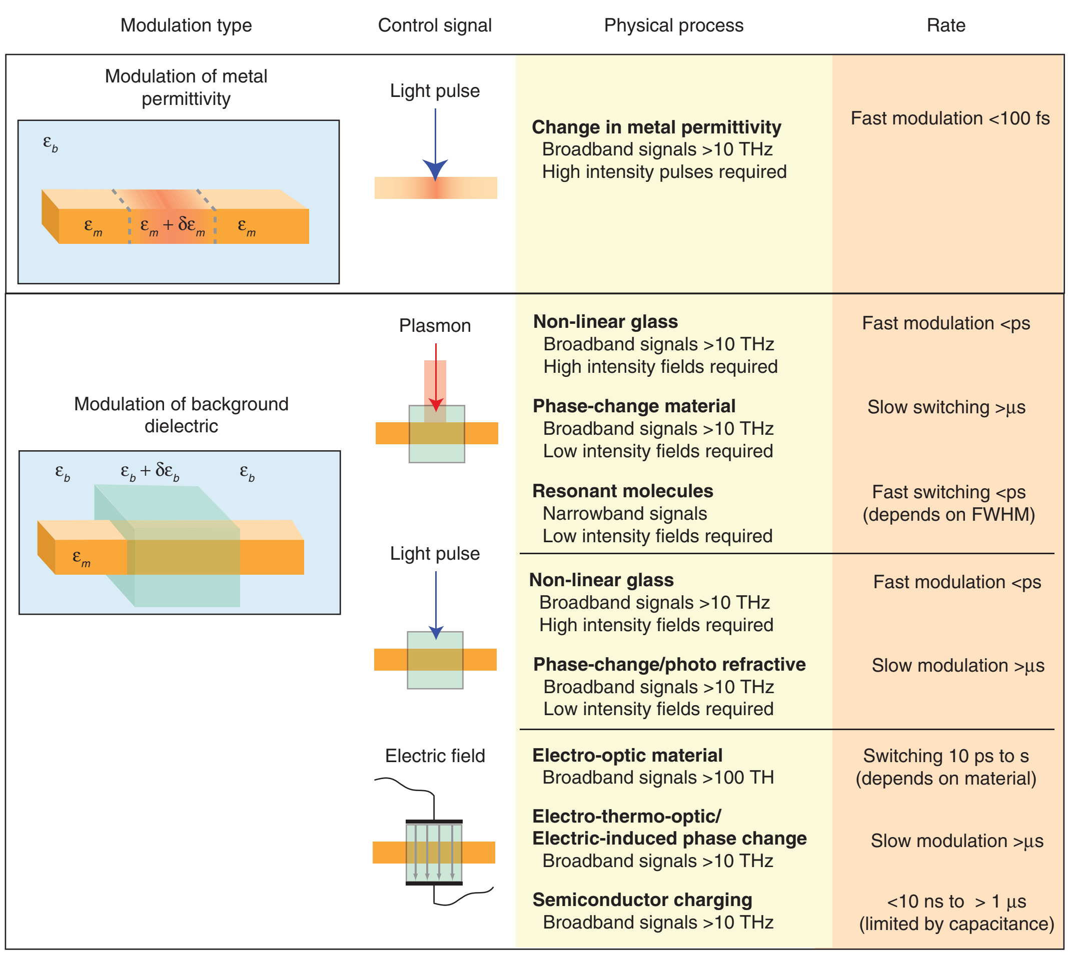

Figure 5: Comparison of plasmon modulation methods.

of most optical materials, which determines the change in refractive index with optical intensity, is in the order of $\sim 10^{-17}$ m^2/W [121]. That is, to change the refractive index by 1% requires light or plasmon intensities around 10^{15} W/m^2. While this is very large, compressing a 1-W laser beam with a cross section area of 1 mm^2 into a region 30×30 nm^2 will create such an intensity. A more practical method for modulating one plasmon by another has been demonstrated using semiconductor nanoparticles, which have an electronic excited state near the plasmon frequency. The excitation of an electron into this state by one plasmon changes the absorption and refractive properties experienced by another plasmon at a different frequency, leading to all-plasmon modulation [122, 123]. An alternative is to use a photochromic dye in which the refractive index is altered by the presence of the plasmon [124] although such processes are slow, taking milliseconds or even seconds to occur.

3.3.2 Modulation by external light

It is well known that light can induce non-linear changes in material properties, which in turn can be used to modify the phase or absorption of propagating electromagnetic waves. In one class of devices, a high intensity light pulse directed onto a metal disturbs the free electron distribution changing the electric permittivity of the metal or an adjacent semiconductor. This is an extremely fast effect, usually induced by femtosecond laser pulses, which perturbs the plasmon [125–128]. A similar effect was observed recently in indium tin oxide nanorods supporting plasmons in the infrared [129]. There are interferometers in which refractive index modulation by a light pulse on a photo-refractive material induces a phase shift in one beam path changing the interference state and therefore the plasmon intensity [130–133]. This method can be used with magneto-optical materials [134]. Light pulses can induce phase transitions in materials, such as vanadium dioxide, which are accompanied by large refractive index changes [135], or light can induce mechanical strain to change the periodicity of a grating, thereby modulating the propagating plasmon [136]. A variant on this method was to use a light pulse to induce scattering centers by the local decomposition of silver oxide [137].

3.3.3 Modulation by an electrical signal

A plasmon ring resonator was constructed with a dielectric host-matrix doped with an electro-optic material that changes refractive index on application of an electrical signal, modulating the plasmon transmission. Such devices can be slow depending on the electrical response time of the material [138]. Recently, a plasmonic Mach-Zehnder modulator was demonstrated, which used an electro-optic material to modulate the phase. The on-chip modulator was integrated into a silicon waveguide of 10-μm length with a frequency response up to 70 GHz [139]. A novel plasmon memory device was based on memristor technology in which the growth of a metal filament under action of an applied electric field modulates the plasmon propagation [140] in a MIM waveguide structure. It is possible to control the electron density by an electric field [141–144] by using a semiconductor or electro-optic material, which can be used to modulate plasmons, or by using Tamm-plasmon-polaritons, which are plasmon states formed at the boundary between a metal and a dielectric Bragg mirror [145]. A similar phenomenon is the Faraday effect in which a static magnetic field applied to a magneto-optic material alters the optical properties, which can be coupled to plasmonic devices [146].

Variants of this method use electrical signals to induce temperature changes that modify the refractive index of a thermo-optic dielectric, again by using interferometry to alter the plasmon intensity [147] or by using electrochemical switching of material properties [148, 149].

It is clear that the most promising methods for plasmon modulation use electrical effects. These are easily integrated into existing electronic circuit designs and can show superior performance [139].

4 Plasmonics as electronics at light frequencies

So far, we have reviewed plasmonics technologies derived from photonics based on waveguide devices such as “Y” junctions, Mach-Zehnder interferometers, and ring resonators. These exploit the wave-like properties of plasmons propagating on surfaces. However, as we discussed in the introduction, it is possible to excite surface plasmons on small metal particles. When illuminated at a specific frequency, LSP resonances are excited (Figure 6A). Physically, these are oscillations of the conduction electrons at the surface of the particle. If we consider these oscillations from the point of view of electrical engineering, we would describe them in terms of traditional circuit elements, such as inductance, capacitance, and resistance.

A correspondence between electrical circuit elements and metal and dielectric particles was given by

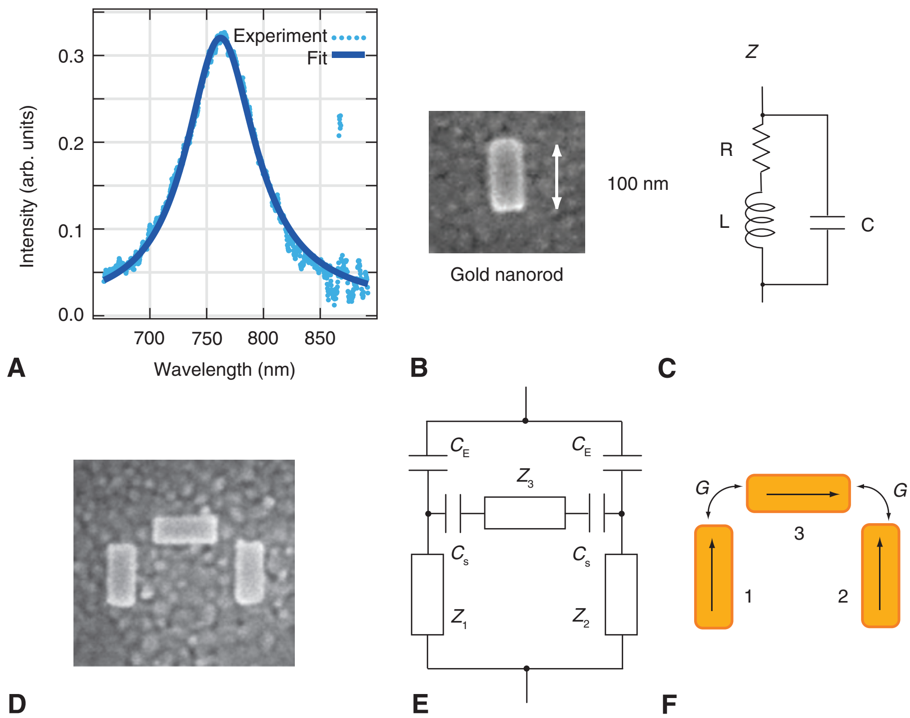

Figure 6: Plasmonics as electronics. (A) An example of the scattering spectrum from a single gold nanorod $l=100$ nm, $w=40$ nm, $t=30$ nm; (B) SEM image of the resist used to define a gold nanorod during lithography; (C) the equivalent circuit impedance of the rod – the spectrum is fit to $I=A+B|Z|^2$ where $Z=(R+j\omega L)/(1-\omega^2 LC+j\omega RC)$ is the circuit impedance. The fit gives the lumped component values $RC=3.99\times10^{-17}$ s and $LC=1.64\times10^{-31}$ s² and the resonant frequency is $f=1/2\pi\sqrt{LC}=393$ THz; (D) a three-nanorod structure that mimics a Wheatstone bridge circuit [150, 151]; (E) the equivalent electrical circuit; (F) an alternative analysis using plasmon coupling theory [152] that gives plasmon excitation amplitude on nanorod 3 $\tilde{a}_3=[Gp\cdot(E_1-E_2)]/[(\delta\omega+i\Gamma/2)^2-2G^2]$ directly in terms of parameters associated with the optics of nanoparticles – the detuning $\delta\omega$ from the single rod resonance of FWHM Γ, dipole moment p and interparticle coupling G. The LSP amplitude depends on the difference in the electric fields E_1-E_2 of the light incident on the two parallel rods, 1 and 2.

Engheta et al. [153, 154] in terms of the electric permittivities and independently by Davis [155] in terms of lumped circuit elements determined from considerations of power flow. This same procedure was used more recently to extract lumped values from complicated arrangements of particles [156]. In essence, a metal particle supporting LSPs can be represented by a combination of inductance, capacitance, and resistance (Figure 6B). The inductance is a consequence of the negative electric permittivity of metals at optical frequencies [154]. The capacitance is related to the influence of the surrounding dielectric, and resistance arises from loss in the metal when a current flows or when the plasmon re-radiates light (radiation resistance). Similarly, a dielectric particle acts like a capacitor [154]. Formulae that accurately predict the circuit values for arbitrary-shaped plasmonic structures are not available. For a metal sphere of radius R and complex permittivity $\epsilon_m=\epsilon'_m+i\epsilon''_m$, the equivalent inductance is given approximately by $L_{\mathrm{sph}}\approx-1/(\omega^2\pi R\epsilon'_m)$, which depends on the real part of the permittivity. The capacitance associated with the external electric fields $C_{\mathrm{fringe}}\approx 2\pi\omega R\epsilon_0$ depends on the permittivity of the surrounding space. The resistance of the sphere depends on the imaginary part ϵ''_m of the permittivity [154].

The plasmon circuit model provides a means for designing optical elements using LSPs in the same way one would design an electrical circuit (Figure 6). This is a radical departure from the usual interpretation of plasmonics as an optical phenomenon and creates new ways of approaching optical information manipulation. The proximity of one metal nanoparticle to another leads to capacitive coupling between the LSPs, mediated by their electric fields. This can result in quite complex circuits and circuit models [156]. The coupling between plasmonic particles is interesting because the resonant modes are altered and generally form pairs that are split in frequency. Such behavior is a consequence of coupled oscillators, well known in physics and engineering. In the study of LSPs, the mode splitting has been described in terms of the hybridization of molecular orbitals that occurs when two atoms bind, which leads to bonding and anti-bonding states [157–159].

The lumped circuit values for plasmonic circuits are generally unknown, and the circuit element associated with a given interaction has to be assumed. Unlike conventional electronics, the inductance of plasmonic particles is strongly dependent on frequency. Furthermore, the role of light polarization on circuit elements is unclear. We developed, as an alternative, an approach based on approximate solutions of Maxwell's equations for the interaction of electromagnetic waves with metal particles. It is possible to write down an equation for the natural resonant modes of an arbitrary shaped metal particle, which becomes relatively simple in the near-field regime where the phase shifts due to propagation of the electromagnetic radiation can be neglected [160–162]. These resonant modes are the LSPs (Figure 2D and E) and are represented by surface charge standing waves. The electric fields from the surface charges couple nearby particles, predominantly through electric dipole interactions. When the coupling between the modes is taken into account, one can derive a simple algebra describing the effects of ensembles of metal nanostructures on one another and on the incident and scattered light fields [152, 163–165]. This is quite analogous to the description in terms of electrical circuits and leads to algebraic expressions no more complicated than those found in electric circuit analysis. The advantage is the algebra is expressed in terms of the natural quantities associated with LSPs, such as electric permittivity, induced dipole moments, and coupling by electric fields including the polarization properties of the incident light fields. This algebraic approach has been very successful and has enabled us to design quite complex circuits, such as the plasmonic Wheatstone bridge that can be used for phase detection [150, 151], all-optical modulation and switching [166], as well as antennas with frequency-dependent beaming [167] and response tailored to the handedness of circular polarization [168].

4.1 Optical antennas

Alongside the development of plasmonic systems as electrical circuits, it has been recognized that metal nanoparticles behave like antennas for light [169, 170]. The optical cross section of a metal nanoparticle is significantly larger than its physical cross section, meaning that a small nano-sized particle can capture light over a much larger area and convert it into a localized plasmon resonance. The simplest optical antenna is a metal nanorod. The fundamental plasmon resonance has a large dipole moment (Figure 2D), and it acts like a half-wave antenna. However, the wavelength corresponds to that of the plasmon and not the incident light, so that optical antennas can have dimensions well below the wavelength of light. Furthermore, the fundamental mode can only be excited by light with an electric field component parallel to the dipole moment, which usually lies along the major axis of the rod, making these optical antennas polarization sensitive. The LSP resonance stores optical energy and, as such, develops very strong electric fields concentrated at the ends of the rod, at least an order of magnitude larger than the electric field of the incident light that excites it. The localization of energy provides efficient coupling of optical energy into other systems, such as waveguides and fluorescent molecules [171, 172], and likewise, the plasmonic antenna can efficiently out-couple radiation from molecules, enhancing emission and polarization characteristics. The quality factor (Q) of the resonance depends on the metal and the dielectric environment but is typically in the range $Q \sim 10$–20.

There has been a large variety of antenna configurations investigated, many of which are based on designs used in radio engineering. As light is an electromagnetic wave, most of the concepts of radio antenna design carry across to the optical domain, except that the conductors are not perfect but are lossy. Optical antennas have been reviewed extensively elsewhere [169, 170, 173], and we give only a brief overview here. Although much has been written on optical antennas, these are essentially metal particles exhibiting LSP resonances and it is more useful to describe them as such. Most optical antenna designs are dipole antennas, even though the antenna geometry can be complicated, as the fundamental resonant mode is predominantly dipolar in nature. Initial studies on optical antennas verified the field enhancement properties of plasmons [174] and the spectral dependence of the antenna near-field [175]. Optical antennas have been used to enhance optical coupling into materials [176], plasmonic waveguides, and transmission lines [177–179]. Examples of different optical antenna designs are the Yagi-Uda antenna [180, 181], cross antennas [182], J-pole [183, 184], V antennas [183], and bow-tie antennas [185]. As with radio engineering, it is possible to create antenna arrays [173] for controlling the divergence and radiation direction of a light beam [186, 187] and plasmonic structures for steering the radiation direction of light depending on frequency [167] or controlling the propagation direction of plasmons based on phase [188]. The antenna excitation patterns [189, 190] can be altered by changing the phase and polarization of the incident light, which affects the plasmon modes that are excited [191].

The antennas can have a strong influence on the optical emission properties of fluorescent molecules

[192, 193], leading to enhanced, polarized, and directed emission, which can be described in terms of impedance matching [194]. Furthermore, such plasmonic antennas can be used to convert polarization states from linear to circular [195] or to distinguish between left and right circularly polarized light [168]. In this regard, a self-consistent electromagnetic theory of the coupling between dipole emitters and dissipative nanoresonators has been developed [63]. The antenna response can be modified by placing dielectric materials or other metals nearby, which affect the LSP resonances. This is analogous to capacitive and inductive loading of the antenna [196, 197]. When loaded with non-linear materials, it has been shown theoretically that optical antennas can exhibit bistability [198]. Tunable plasmonic antennas were created from two suspended wires and changing their separation with an applied voltage [199].

4.2 Plasmonic circuits

There has been relatively little work relating plasmonics to electronics and building devices using this concept. The concepts of distributed electronic circuit components have been applied to optical structures such as transmission lines [153, 200], and an analysis of the optical power associated with electromagnetic waves can be related to lumped circuit components [155, 156, 201]. The lumped circuit description has been demonstrated in the optical regime (below 700 nm) in terms of an inductor-capacitor circuit [155] in the thermal infrared regime (8–14 μm) [202] and mid infrared (above 1.3 μm) [203].

Simple plasmonic circuits have been shown to act as filters for waveguides [204] or for loading antennas [196, 197], as well as mimicking more complex filters, such as a third-order Butterworth filter [205]. The correspondence between metal and dielectric particles and electronic components has been demonstrated using a scanning probe tip to assemble together different optical filter combinations [206]. That the optical resonances of metal nanoparticles can be altered in the presence of other metals or dielectrics is well known so it is not surprising that optical filters can be created in this way.

There are very few complex plasmonic circuits demonstrated with specific functionality. The plasmonic equivalent of the Wheatstone bridge circuit in electronics was suggested as a means for detecting optical signal differences [150], and a realization of the circuit with dimensions around 200 nm acts as an optical differentiator to detect optical phase differences [151]. Circuits of this type have potential applications in optical signal processing, such as decoders for differential phase-shift keying. The plasmon coupling theory [152, 163, 164] shows that such plasmonic circuits output signals that are linear combinations of the inputs $E_{out} = \bar{M} \cdot E_{in}$, but with complex matrix coefficients $\bar{M}$ [166], which suggests that a variety of different linear mathematical operations can be performed. This plasmon circuit concept was used to design a device for all-optical modulation of light, based on an interference effect, as well as all-optical switching of light beams [166].

The idea of performing mathematical operations on light fields using nanoscale structures was highlighted recently where optical Fourier transforms were demonstrated numerically [207]. In addition to the optical differentiator described above [151], designs for an optical differentiator and integrator were demonstrated [208], providing an approach to analogue optical computing.

5 Quantum plasmonics

Although plasmon properties can be described by classical electromagnetism, the plasmons arise from long-range correlations of the conduction band electrons in a metal and appear in the form of quasi-particle boson states with both particle and wave-like properties. In particular, the plasmons remain coherent with the incident light, suggesting that it should be possible to observe quantum coherence effects with them or to use plasmons for manipulating quantum properties of light. The resurgence of interest in plasmonics has been accompanied by an interest in their quantum properties [59, 209], which includes coherence, entanglement, and wave-particle duality [209]. Plasmon waveguides have been used to observe quantum interference [65] as well as two plasmon quantum interference [210]. The wave-particle duality of single SPPs has been studied using single photon emitters coupled to a silver plasmon waveguide [57]. The quantum tunneling of electrons across sub-nanometer gaps between coupled plasmonic particles has been investigated [211]. Plasmons also couple to quantum systems, such as semiconductor nanocrystals [212, 213]. The strong coupling between individual optical emitters and propagating surface plasmons has been proposed as an interface for quantum networks [214].

6 New materials

A major issue with both classical and quantum plasmonic devices is loss due to electron decoherence, which is followed by absorption of energy in the metal lattice. This destroys the coherence of the plasmon quantum state. This problem of energy loss in the metal also limits the use of plasmonic devices in telecommunications, which often demands low loss materials and low insertion loss. While active media or stimulated emission [43, 53] may overcome losses, an alternative has been to seek low loss materials that support plasmon resonances [215]. The key material property required for plasmonic behavior is an electric permittivity that is negative over a range of frequencies. A review of work on new materials [216] discusses the advantages and disadvantages of various metals and semiconductors with the conclusion that silver, gold, and aluminum are still the best materials for SPPs and LSP resonances in the visible and ultraviolet regions. Recently, titanium nitride was identified as a promising material for the visible and near infrared regions [217] although it has a smaller electric permittivity and greater losses when compared with gold at the same frequency. In this regard, gold is a better material for plasmonics.

7 Outlook

Despite the initial promise of plasmonics for nanoscale optical devices, there are disappointingly few commercial applications of plasmonics and none in the communications field [218, 219]. Most of the devices presented in this review have scientific interest, but few are practical solutions to photonics problems. Certainly, for plasmonics to have some future in optical signal processing, it is important that methods and materials are developed for better integration with existing communications technology. In this regard, devices such as the all-plasmonic Mach-Zehnder modulator that was constructed on a silicon chip show promise [139].

For optical signal processing or optical computing based on plasmonics, logic and computational operations need to be developed using current encoding schemes instead of just phase. With the advantage of far lower losses than metals, dielectrics are likely to play an increasing role in all-optical processing. Recent developments in silicon technology for the telecommunications wavelengths are now competing with plasmonic devices. These on-chip silicon devices, such as a wavelength demultiplexer and a polarization beamsplitter, have small footprints and are composed entirely of dielectrics [220]. However, plasmonic devices, with smaller resonator sizes, subwavelength size scales, and potential for compatibility with conventional CMOS processing techniques, may still have an important place in this emerging and exciting field.

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