A truly one-way lane for surface plasmon polaritons

Unidirectional and topological surface plasmon polaritons are currently attracting substantial interest and intense debate. Realistic material models and energy conservation considerations are essential to correctly understand extreme wave effects in non-reciprocal plasmonics, and to assess their potential for novel devices.

Francesco Monticone

Research interest in non-reciprocal plasmonics is motivated by the many opportunities offered by combining the benefits of plasmonic structures, namely sub-diffractive light confinement and giant local-field enhancement, with the rich physics of non-reciprocal and topological materials. While the surface-wave propagation on non-reciprocal (magnetized) plasmas is a well-studied topic, with foundations dating back more than half a century[1–3], the current wave of interest is focused on the investigation of truly unidirectional surface plasmon polaritons (SPPs), their non-trivial topological properties and their counterintuitive implications in certain peculiar configurations[4–23].

Unidirectional SPPs on non-reciprocal plasmonic platforms represent a highly non-trivial regime of light propagation, with potential importance for realizing compact and robust devices for classical and quantum information processing, including compact non-reciprocal devices for Faraday rotation, isolation and circulation[5,7,8], backscattering-immune wave propagation and light–matter interactions robust against disorder[4,6,9–13], as well as non-reciprocal cavities exhibiting an apparent violation of the lifetime–bandwidth constraints of resonant structures[14]. At the same time, a few recent studies have argued that some of these exciting opportunities are based on non-physical assumptions, disputing the existence of strictly unidirectional SPPs in certain configurations[18,21], and ruling out the possibility of breaking the time–bandwidth limit in linear, time-invariant, non-reciprocal plasmonics[15,17,18].

This Comment seeks to give a concise overview of the current state of this dynamic and exciting area of research. I elucidate whether strictly unidirectional SPPs exist in non-reciprocal plasmonics, and clarify their behaviour and implications.

How to open a unidirectional frequency window

A direct consequence of time-reversal symmetry for wave propagation — equivalent to Lorentz reciprocity in the lossless case — is that the dispersion diagram of most conventional photonic structures is symmetrical, $\omega(\mathbf{k}) = \omega(-\mathbf{k})$, where ω and $\mathbf{k}$ are the frequency and wavevector, respectively, of a mode of the system. All isotropic dielectric or plasmonic materials are reciprocal, and so are all the anisotropic crystals used to make, for example, wave plates. The dispersion diagram may become asymmetrical only by breaking reciprocity, which requires biasing the system with a physical quantity that is odd upon time reversal — usually a static magnetic field — or by breaking the time-invariance of the system. However, non-reciprocity alone is not sufficient to obtain modal unidirectionality. The opening of a unidirectional frequency window, in which propagation is strictly forbidden in either the forward or backward direction, requires a 'strong form' of non-reciprocity, in which the asymmetry of the dispersion diagram is maximized by some other suitable effect.

Indeed, while a photonic band cannot simply disappear at a certain frequency, the mode may become evanescent, that is, with imaginary wavenumber, if it enters a photonic bandgap or if it exhibits a cut-off frequency. Considering the limit of vanishing loss, including radiation loss, for simplicity (the effect of dissipation is discussed below), the longitudinal modal wavenumber k is either purely imaginary or purely real. Hence, in a lossless system with continuous translational symmetry, the transition from propagating to evanescent waves can only happen, at a given frequency, if the modal wavenumber vanishes or diverges. This can be understood by considering a Riemann sphere representation of the extended complex plane of the longitudinal wavenumber (that is, the complex plane with the point at infinity attached, which can be mapped to a spherical surface, the Riemann sphere, by a stereographic projection). From this representation, one can see that it is necessary to either pass the point at $k = 0$ or the point at infinity to move, directly, from the real to the imaginary axis.

A frequency range in which propagation is strictly forbidden can therefore be accessed, in the lossless limit, in two cases. In the first case, the photonic band has a flat asymptote for $k \to \pm\infty$ (vanishing phase velocity). This is the behaviour, for instance, of conventional SPPs at the surface plasmon resonance for a lossless Drude plasma. In the second case, the band goes under cut-off at $k = 0$ (diverging phase velocity), as in the case of conventional non-transverse-electromagnetic waveguide modes at their cut-off frequency.

In order to open a unidirectional frequency window for a guided mode, the mechanism that breaks reciprocity, for example, a magnetic bias, should therefore act to introduce an asymmetry in the flat dispersion asymptotes or in the cut-off frequencies of backward- and forward-propagating waves. Depending on whether the unidirectionality originates from the dispersion behaviour at small or large wavenumbers, the impact of dissipative and non-local effects on a one-way guided mode may be markedly different, as discussed in the following.

Unidirectionality based on the dispersion behaviour for large k

In the classical case of SPPs at an interface between a plasmonic material and an isotropic dielectric, the application of a magnetic bias to the plasma makes the SPP dispersion strongly asymmetrical, with maximal asymmetry in the plane orthogonal to the bias (Voigt configuration), as the electrons moving in this plane feel the magnetization most strongly. In particular, the bias shifts the surface plasmon

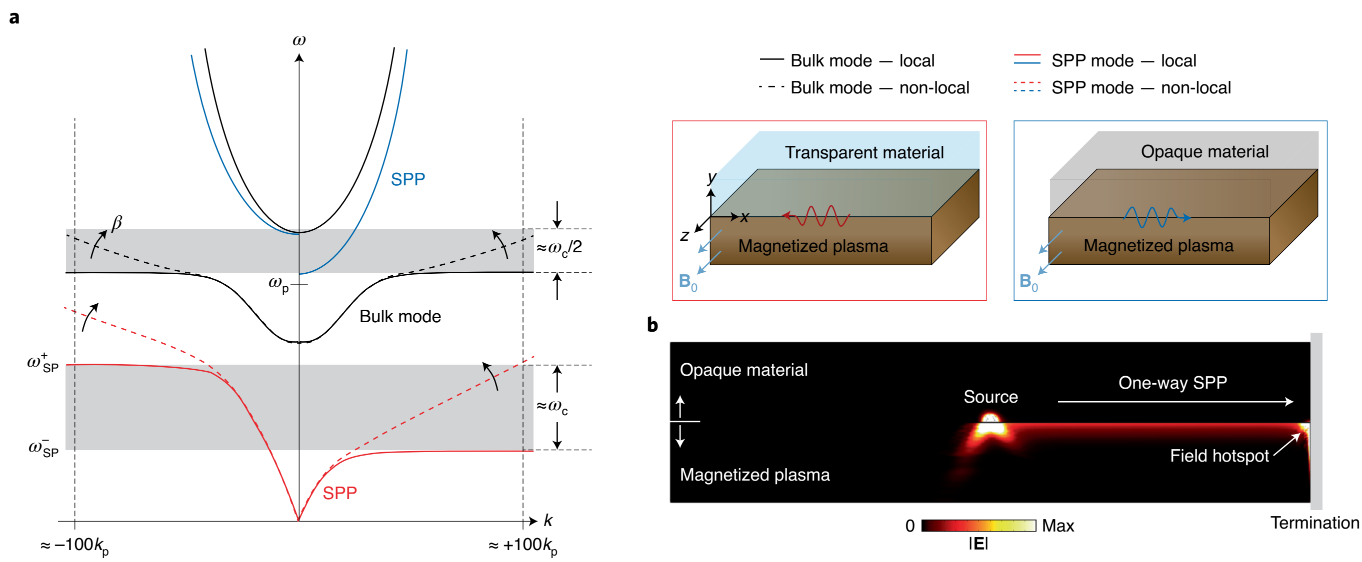

Fig. 1 | Unidirectional SPPs. a, Illustration of the typical band diagram of a non-reciprocal plasmonic platform in the local and non-local cases (in the limit of vanishing losses). Black curves indicate the bulk modes of a three-dimensional magnetized plasmonic material, in the plane orthogonal to the bias $\mathbf{B}_0$ (the curves delimit the region of the projected bulk bands). Red/blue curves denote the SPPs supported by an interface between the biased plasma and a transparent or an opaque material, respectively (corresponding to the red/blue inset boxes to the right). Solid lines, local case; dashed lines, non-local (hydrodynamic) case. k is the SPP wavenumber in the longitudinal x-direction, and k_p is the free-space wavenumber at the plasma frequency ω_p. The arrows next to each dashed line indicate the upward bend of the dispersion curves as the non-local parameter β increases. Shaded grey areas indicate the unidirectional frequency windows, which are closed by non-local effects for values of wavenumber typically comparable or larger than $100\omega_p/c_0$ (refs. [18,21]), as indicated by the vertical dashed lines. **b**, One-way SPP incident on an ideal termination, forming an intense field hotspot as the wavelength shrinks[16,17,21]. The colours represent the intensity of the electric field **E**. Panel **b** adapted with permission from ref. [21], The Optical Society.

resonance from its conventional value in the reciprocal case, ω_{SP}, to different values for forward- and backward-propagating modes, $\omega^{\pm}_{SP} \approx \pm\omega_c/2 + \omega_{SP}$, where ω_c is the cyclotron frequency, proportional to the bias intensity, assumed here to be much smaller than the plasma frequency ω_p. Hence, a unidirectional frequency window is opened, with bandwidth equal to ω_c, defined by the asymptotically flat bands at $\omega^{\pm}_{SP}$, as illustrated in Fig. 1a.

This biased-induced asymmetry in the surface plasmon resonance is the conventional strategy to realize unidirectional surface magneto-plasmons, which have been studied since at least the 1970s[3], and are at the basis of several counterintuitive effects, including the apparent violation of the time–bandwidth limit recently reported in ref. [14]. However, it was recently argued in ref. [18] that the flat asymptotic dispersion that is at the very basis of this form of unidirectionality is non-physical. This can be understood from general thermodynamics considerations: a system supporting a mode with bounded dispersion, $\omega(k) \in [0, \omega_{SP}]$, over an unbounded wavenumber range, $k \in [0, \infty)$, would have infinite photonic states in the range $[0, \omega_{SP}]$. Thus, as discussed in ref. [18], the electromagnetic energy density of the system would be infinite at a finite temperature, which is clearly unphysical.

The problem arises from employing a local and lossless Drude model for the plasmonic material, which is too simplistic to make correct predictions in this scenario. The locality assumption, namely, the fact that the material response is a delta function in space (hence, independent of **k**), is inadequate when considering modes with large wavevector, for which non-local effects (spatial dispersion) tend to suppress the material response[9,24]. The non-local response of a plasmonic material is primarily due to the movement of free electrons during an optical cycle not caused by electric-field-induced drift, but by convection and diffusion, which act to homogenize any inhomogeneity in the electron density[24]. Different models of non-locality have been proposed in the literature, among which the so-called hydrodynamic model is arguably the most popular. This is based on treating the electron gas semi-classically as a hydrodynamic fluid with a pressure term whose intensity is proportional to the Fermi velocity (inversely proportional to the electron effective mass)[24]. Hydrodynamic non-locality affects the longitudinal part of the modal electric field, which becomes especially important for transverse-magnetic modes having flat asymptotic dispersion.

Indeed, when non-local effects are incorporated in the analysis of unidirectional surface magneto-plasmons on a non-reciprocal plasma, the unphysical flat asymptotic dispersion is removed, as demonstrated in ref. [18], and further confirmed in ref. [21], using a hydrodynamic model for the non-locality of magnetized n-type InSb. The corrected SPP dispersion diagram is illustrated in Fig. 1a (dashed red curves): the unidirectional frequency window is closed by the upward bend of the right-going mode for large wavenumbers. Hence, SPPs are allowed, in principle, to propagate in both directions at all frequencies.

Different models of non-locality, and different choices of boundary conditions (including, for instance, the effect of electron spill-out[25]) are expected to produce moderately different results, and the area of non-reciprocal plasmonics can certainly benefit from more accurate microscopic and quantum-plasmonic models, beyond the hydrodynamic treatment. Nevertheless, the observations above are more general than the specific model of non-locality considered in these studies. Indeed, general phenomenological considerations of

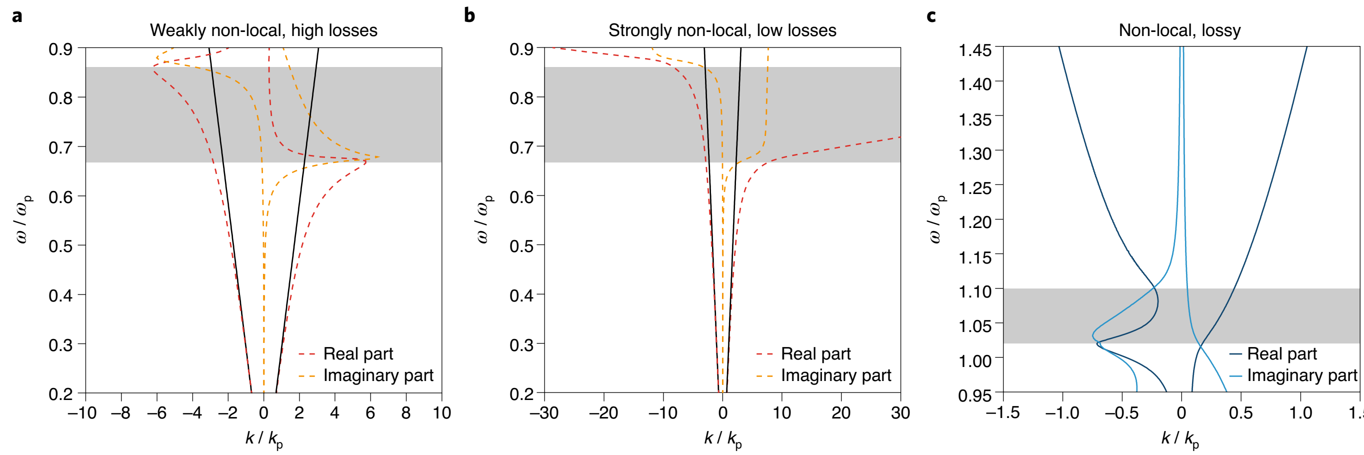

Fig. 2 | Impact of dissipation and non-locality. a,**b**, Complex dispersion diagrams (complex wavenumber and real frequency) for surface magneto-plasmons in the dissipative scenario, for two limiting cases: high losses and weak non-locality (**a**), low losses and strong non-locality (**b**). As discussed in the text, whether the effect non-locality or dissipation dominates depends on the specific material. Solid black curves represent the light lines in the transparent material. **c**, Complex dispersion diagram for topological SPPs in the dissipative non-local scenario. The impact of non-locality is minimal in this case. The shaded grey areas indicate the unidirectional frequency windows.

non-locality show that the leading-order non-local correction to the local-response electrodynamics is always $O(k^2)$, as in the hydrodynamic model, irrespective of the microscopic mechanism of non-locality[26]. As an aside, it is also noted that the singular and paradoxical response of certain exotic metamaterials can often be regularized in a similar fashion by including non-locality (or loss). This is the case, for example, of the broadband density-of-states singularity exhibited by hyperbolic metamaterials in the local-response approximation, which is regularized by the introduction of non-local effects and the resulting large-wavevector cut-off in the material response[27].

The impact of dissipation (electron scattering, radiation loss and surface-induced Landau damping) should also be carefully assessed, as it prevents the SPP from reaching very large values of wavenumber. In the local dissipative case, close to $\omega_{SP}^{\pm}$, the SPP dispersion exhibits a so-called 'back-bending', as Re[k] decreases after reaching a maximum value, while the damping, Im[k], strongly increases in the same region. In the non-local case, dissipation may actually restore unidirectionality, since the non-locality-induced right-going mode gets attenuated more strongly than the left-going mode. Indeed, for moderately high levels of loss and weak non-locality, the surface magneto-plasmon dispersion exhibits a similar back-bending as in the local case. In this scenario, as shown in Fig. 2a, the left-going mode is underdamped (Re[k] > Im[k]) within the unidirectional frequency window, whereas the right-going mode is overdamped (Re[k] < Im[k]). The latter is, therefore, suppressed by dissipation, restoring unidirectionality for all practical purposes. Conversely, if the loss level is low, or non-local effects are particularly strong, as in the case of solid-state plasmas with low effective mass (for example, n-InSb), the right-going mode may remain underdamped, as discussed in ref. [18] and shown in Fig. 2b. The mutual competition of non-locality and damping illustrated in Fig. 2a,b is analogous to a competition observed in reciprocal plasmonic systems (see, for example, ref. [28]), with the main difference being the strong asymmetry of the dispersion diagram in the non-reciprocal case.

In summary, while surface magneto-plasmons cannot be considered strictly unidirectional, in practice the actual impact of non-locality relative to the effect of dissipation should be carefully assessed for different plasmonic materials.

Unidirectionality based on the dispersion behaviour for small *k*

The SPPs considered above, while arguably the most studied in the literature, are not the only form of surface modes supported by plasmonic platforms. If the material interfaced with the magnetized plasma is not a dielectric, but a reciprocal (that is, unbiased) metal with higher plasma frequency, the interface now supports SPPs in the frequency range between the plasma frequencies of the two materials. In this range, while the reciprocal metal is still opaque, the magnetized plasma is generally not, but it exhibits, in the local case, a bandgap for the bulk modes that is opened by breaking time-reversal symmetry. At frequencies within this bulk-mode bandgap, the SPPs supported by the metal/metal interface are unidirectional, as illustrated in Fig. 1a (blue solid curves). This fact has been known since the 1960s in studies of gyrotropic plasma sheaths on a metallic surface[1,2].

It was then shown in refs. [9,11,19,20] that the unidirectional nature of SPPs of this type stems from the non-trivial topological properties of the upper bulk-mode bandgap of the magnetized plasma, which is characterized by an integer non-zero topological invariant — the gap Chern number — that can change only if the bias is switched off or reversed. As in quantum-Hall topological insulators, at the interface between materials having different gap Chern numbers, unidirectional surface states may emerge that are topologically protected and backscattering immune, as dictated by the so-called bulk–edge correspondence principle. The interested reader may refer to ref. [22] for further details on this principle, and to ref. [23] for a discussion of some apparent violations and anomalies in continuous media. Conversely, the surface magneto-plasmons supported by dielectric/metal interfaces, discussed in the previous section, are not topological, since they exist in a topologically trivial bulk-mode bandgap (lower bandgap of the magnetized plasma) and the transparent medium at the interface does not have a bulk-mode bandgap in the same frequency region[11,21].

The robust unidirectionality of topological SPPs on metal/metal interfaces can also be understood, in simpler terms, by recognizing that, unlike surface magneto-plasmons, these surface modes have a lower-frequency cut-off, below which the mode is evanescent. The application of the bias makes the cut-off frequencies asymmetric, opening a unidirectional frequency window, $\sqrt{\omega_c^2+\omega_p^2}<\omega<\omega_c/2+\sqrt{\omega_c^2/4+\omega_p^2}$, where only the forward-propagating SPP is above cut-off and is allowed to propagate, as illustrated in Fig. 1a. Thus, the unidirectionality of these SPPs does not depend on a non-physical flat dispersion for large wavenumbers, but rather on an asymmetry in modal cut-offs for small wavenumbers, which suggests that they may be much more robust to non-locality and dissipation. It was recently shown in ref. [21] that this is indeed the case: the unidirectional SPPs existing at a plasma/plasma interface, within the bulk-mode bandgap, are almost completely unaffected by spatial dispersion, even considering the strong non-locality of a solid-state plasma such as n-InSb.

It should also be noted that the full bulk-mode bandgap is not generally preserved in the non-local case: the flat asymptotic dispersion of the lower bulk mode is strongly affected by non-locality, which causes the mode to bend upward for large values of k, as illustrated in Fig. 1a (black dashed curves). For a typical sample of n-InSb, this non-local correction becomes important only for large values of wavenumber on the order of tens of ω_p/c_0 (ref. [21]). The main effect of this behaviour is that the unidirectional SPP becomes, in general, a leaky wave, damped by radiation into the magnetized plasma since the SPP can now couple to the bulk mode at certain angles (as dictated by transverse momentum conservation). Non-locality-induced leakage was already recognized in early works on surface waves supported by metal/metal interfaces[29]. In practice, however, it was found in ref. [21] that the leakage is negligible at frequencies where the SPP mode is unidirectional, while it becomes important at higher frequencies.

Finally, also for this type of SPPs, the impact of absorption losses should be carefully investigated to understand whether their unidirectionality is robust to dissipation. As shown in Fig. 2c, both dispersion branches continue below cut-off in the lossy case. In other words, the longitudinal wavenumber k is no longer purely imaginary below cut-off and purely real above; instead, k is always a complex number, representing a damped propagating mode, consistent with the response of lossy waveguides near cut-off. Nevertheless, it is clear from Fig. 2c that, while the forward-propagating SPP is underdamped ($\mathrm{Re}[k] > \mathrm{Im}[k]$), the backward-propagating SPP is overdamped ($\mathrm{Re}[k] < \mathrm{Im}[k]$) over the entire bulk-mode bandgap. In this sense, therefore, the system remains unidirectional even in the presence of dissipation.

Different variations of the configuration discussed here exist, with, for example, the two plasmonic materials both magnetized in opposite directions, or with a subwavelength dielectric gap between the metals; however, similar considerations are expected to apply to all these cases, as long as the SPP unidirectionality is based on the dispersion behaviour for small wavenumbers. Interestingly, while all the cases discussed here refer to SPPs existing on the surface of three-dimensional plasmonic platforms (in the plane orthogonal to the bias), two-dimensional electron gases (for example, graphene) under a magnetic bias have also been shown to support one-way edge SPPs with an analogous topologically robust behaviour[10].

Terminated one-way channels and non-reciprocal cavities

Unidirectional modes, which typically propagate seamlessly around bends and discontinuities, can be fully stopped by introducing certain suitable terminations (Fig. 1b). For example, a metallic wall orthogonal to the plasma/dielectric interface can be used to stop unidirectional surface magneto-plasmons[14,17,18,21]. Since the wall itself does not support propagating waves on its surface, it is relevant to wonder what happens to the energy carried by a unidirectional surface wave as it impinges on the termination. Consistent with the fact that a linear optical isolator can offer ideal isolation only in the presence of some form of loss, the wave incident on the termination sees different loss channels, which include not only material absorption, but also the non-locality-induced backward-propagating mode or the radiation leakage discussed in the previous sections.

Interestingly, however, even if non-local effects or dissipation are assumed negligible, a configuration of this type still has another often-neglected loss channel. The wave approaching the termination sees a plasmonic corner, or wedge, with shrinking size, which has the effect of continuously reducing the SPP wavelength and lowering its group velocity. As shown in Fig. 1b, this so-called 'wedge mode' creates an intense field hotspot, due to the accumulation of energy at the termination, which is ultimately dissipated completely, regardless of the level of losses, as discussed in refs. [16,17,21]. This is true even in the limit of vanishing losses, as recognized since the pioneering work of Ishimaru, Barzilai, and others in the 1960s[1,30]. While the problem of an ideally lossless, terminated, one-way channel is an ill-posed boundary-value problem, in the limit of vanishing losses the dissipation in the wedge mode can be shown to be finite[1,17]. In a sort of modern-day Zeno's paradox, the wave never truly reaches the termination as its wavelength continuously shrinks and its group velocity lowers. Furthermore, this behaviour is relatively broadband since it can occur over the entire unidirectional frequency window of the non-reciprocal system, and does not rely on resonant effects. This is analogous to the broadband focusing of energy in conventional adiabatic plasmonic tapers[31], but facilitated here by the non-reciprocal nature of the channel, which ensures automatic impedance matching.

Interestingly, it was recently argued that, if a one-way channel is terminated by a closed cavity, it may appear that the in-coupling rate of the energy into the cavity is different from the out-coupling rate, which was proposed as a mechanism to break the well-established lifetime–bandwidth limit for resonant cavities[14]. Unfortunately, however, this is not possible. As fully elucidated in ref. [17], both the lifetime and bandwidth of a cavity resonance depend on the total out-coupling rate and, more generally, the time–bandwidth limit cannot be violated in any time-invariant system, reciprocal or not[17,18,32]. Moreover, if a passive cavity, reciprocal or non-reciprocal, has one port, the in-coupling and out-coupling rates at that port must always be equal in magnitude, otherwise the system would never reach equilibrium (steady state) as the energy stored in the cavity would build up indefinitely. Unequal in-coupling and out-coupling rates at an individual port can be obtained only if more than one channel is connected to the cavity, while the total input and output rates must always remain equal to respect energy conservation in a passive system[15,17]. These additional ports are provided by external loss channels, which also include the non-locality-induced propagation/radiation channels and the wedge mode discussed above.

These considerations further illustrate the counterintuitive behaviour of non-reciprocal plasmonic systems, and confirm the importance of accurately modelling their rich physics.

Conclusion and parting thoughts

The growing number of publications on anomalous effects in non-reciprocal plasmonics indicates how dynamic and fertile this area of research has recently become. As discussed in this Comment, one key conclusion of recent work in this area is that the impact of non-locality and dissipation on one-way SPPs strongly depends on the considered structure and regime of operation[18,21]. In addition, even if all materials are assumed perfect, with zero intrinsic bulk losses, plasmonic platforms can never be treated as ideally lossless, since non-locality-induced radiation loss and, especially, confinement-induced Landau damping always need to be taken into account to avoid incorrect predictions[23,33,34]. Another important finding of recent work in this area is that non-reciprocal plasmonic systems are still subject to the same time–bandwidth constraints of reciprocal systems, unless linearity and/or time-invariance are also broken[17,32]. This conclusion is true for any system, but it becomes particularly important in the context of non-reciprocal plasmonics, where extreme field localization and enhancement, as in the case of the plasmonic wedge mode mentioned above, may exacerbate the difficulties in interpreting the behaviour of non-reciprocal waveguides and resonators. One can also speculate that the ultra-strong, broadband and highly confined field hotspots obtained in terminated one-way plasmonic channels may be useful, under certain conditions, to drastically enhance linear and nonlinear light–matter interactions.

It must be stressed that classical macroscopic electrodynamics, combined with energy conservation considerations, is typically sufficient to clarify, self-consistently, the behaviour of seemingly paradoxical situations, as in the case of a terminated one-way channel or a non-reciprocal cavity, without the need of relying on microscopic descriptions of the involved materials. At the same time, as concluded in ref. [18], more realistic material models, based on microscopic and quantum-plasmonic considerations, are important for more accurate and quantitative predictions of extreme non-reciprocal plasmonic effects in practical scenarios. ❐

Francesco Monticone ✉

School of Electrical and Computer Engineering, Cornell University, Ithaca, NY, USA.

✉*e-mail: francesco.monticone@cornell.edu*

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