Topologically Protected Unidirectional Surface States in Biased Ferrites: Duality and Application to Directional Couplers

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***Abstract*—We demonstrate theoretically the existence of a unidirectional surface mode at the interface between a gyromagnetic medium (biased ferrite) and a magnetically opaque medium, occurring in the frequency gap of the bulk medium. The topological invariant of the gyromagnetic medium, the Chern number, is calculated analytically from the bulk dispersion bands, and duality is used to connect with the previously studied gyroelectric (magnetoplasma) case. The surface wave transmits electromagnetic energy without any backscattering or radiation, even in the presence of arbitrarily large physical perturbations at the interface. An application to a surface-plasmon directional coupler with perfect isolation is proposed.**

***Index Terms*—Biased ferrite, Chern number, directional coupler (DC), time reversal (TR), unidirectional surface plasmon.**

I. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves that are confined to material interfaces and allow subwavelength confinement of light [1]. Extensive research has been carried out in this field due to its technological potential. Applications of SPPs in electronics and optics are numerous, and include light harvesting [2], medical sciences [3], plasmon focusing [4], and waveguiding and interferometry [5]. However, all plasmonic devices are impacted by SPP reflection, radiation, and diffraction at surface defects and discontinuities. In particular, for reciprocal materials, for each forward propagating mode, there is a corresponding backward mode with identical propagation constant and modal distribution, and a surface defect/discontinuity can both scatter a forward mode into a backward mode (and vice versa) and cause significant radiation/diffraction of the SPP into the bulk materials. In order to control this effect, we have to: 1) eliminate one of the modes (forward or backward), and 2) ensure that energy is not radiated into the bulk materials. The presence of a backward state comes from time-reversal (TR) symmetry; when broken, a backward state may be absent, and reflection at a discontinuity can be suppressed. Furthermore, if the surface mode appears in a common band-gap of both bulk materials, then at a surface, discontinuity radiation/diffraction into the bulk is suppressed. As a result, surface energy is unidirectional and must follow the contour of the interface, even in the presence of strong discontinuities. This type of system can be broadly classified as a photonic topological insulator (PTI) [6], which is an electromagnetic insulator in its bulk with conducting states on its surface. The first PTIs were considered in [7] as analogs to electronic topological insulators, in which surface electron transport occurs without dissipation, even in the presence of impurities. Furthermore, these electronic states are topologically protected, meaning only system perturbations that change the material topology (e.g., close a band-gap) and can affect the transport. A common way to break TR is via a magnetic bias field applied to a ferrite or plasma [8]–[12]. Although the resulting material is nonreciprocal, in certain configurations (e.g., the Voigt configuration considered below) the bulk modes are reciprocal due to symmetry. However, an interface can break symmetry and results in nonreciprocal behavior of surface waves [13]. Unidirectional surface modes in magnetized plasma systems have been well studied [14]–[17], but there has not been similar consideration of gyromagnetic systems such as biased ferrites, which are important materials at microwave frequencies.

In this letter, we demonstrate the presence of a topologically protected, unidirectional surface wave at microwave frequencies using a magnetized ferrite. We calculate the Chern number, which is the topological invariant related to the behavior of the bulk dispersion bands, and which is used to characterize the number of one-way surface modes. We discuss duality with the previously studied biased plasma case, and consider application of these unidirectional surface modes to a plasmonic directional coupler. We consider a magnetoplasma coupler for the THz regime, where surface plasmons are particularly important, although, by duality, one can achieve the same type of coupler in the microwave regime using ferrites. Both types of gyrooptic materials represent promising platforms for a variety of applications in waveguiding and wave isolation. The time convention $e^{-i\omega t}$ is assumed.

II. Fundamental Equations

Defining the Hermitian electromagnetic tensor

$$\mathbf{\Lambda} = \begin{bmatrix} \kappa & -i\chi & 0 \\ i\chi & \kappa & 0 \\ 0 & 0 & \delta \end{bmatrix} \tag{1}$$

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where κ, χ, and δ are generally lossless yet dispersive functions, a typical gyromagnetic material, such as a ferrite, is characterized by $\epsilon = \epsilon_0 \epsilon_r$, $\underline{\mu} = \mu_0 \mathbf{\Lambda}$, and a typical gyroelectric material, such as a magnetized plasma, is characterized by $\underline{\epsilon} = \epsilon_0 \mathbf{\Lambda}$, $\mu = \mu_0 \mu_r$. As discussed later, these materials are duals of each other, and (1) represents both material types when a bias magnetic field is applied along the z-axis. Considering wave propagation in the xoy-plane with no variation along the z-direction ($\partial/\partial z = 0$), it can be shown that plane waves supported by a gyromagnetic medium decouple into TE (E_z, H_x, H_y) and TM-modes (E_x, E_y, H_z); this is the magnetic analog of the Voigt configuration for a magnetoplasma. By solving Maxwell's equations, it can be shown that the TM mode with dispersion equation $k^2 = \delta(\frac{\omega_n}{c})^2$ is a simple mode while the TE-mode has nontrivial dispersion

$$k^2 = \mu_{\mathrm{eff}}\, \epsilon_r \left(\frac{\omega_n}{c}\right)^2 \tag{2}$$

where $\mu_{\mathrm{eff}} = (\kappa^2 - \chi^2)/\kappa$, ω_n are the TE-mode eigenfrequencies, and c is the speed of light in vacuum. Despite the anisotropic nature of the permeability, both modes are isotropic due to symmetry. This can be broken at an interface (y normal) between a gyromagnetic medium and a magnetically opaque medium. The dispersion equation of the TE-SPP at the interface is

$$\frac{\alpha_s}{\mu_s} + \frac{\alpha_f}{\mu_{\mathrm{eff}}} = \chi \frac{k_{\mathrm{spp}}}{\kappa \mu_{\mathrm{eff}}} \tag{3}$$

where $\mu_s < 0$ is the permeability of the magnetically opaque medium, and $\alpha_s = k_0 \sqrt{(k_{\mathrm{spp}}/k_0)^2 - \mu_s}$ and $\alpha_f = k_0 \sqrt{(k_{\mathrm{spp}}/k_0)^2 - \epsilon_{\mathrm{eff}}}$ are the attenuation constants in the magnetically opaque and gyromagnetic mediums, respectively.

A. Duality

Although we are interested in the gyrooptic cases described above, for generality, we can consider a bianisotropic material characterized by the 6×6 matrix

$$\mathbf{M} = \begin{pmatrix} \epsilon_0 \underline{\epsilon} & \frac{1}{c}\underline{\xi} \\ \frac{1}{c}\underline{\varsigma} & \mu_0 \underline{\mu} \end{pmatrix} \tag{4}$$

where $\underline{\epsilon}$, $\underline{\mu}$, $\underline{\xi}$, $\underline{\varsigma}$ are dimensionless, real-valued tensors representing permittivity, permeability, and magneto-electric coupling. The duality transformation for this medium implies [18] $(\mathrm{E},\ \mathrm{H},\ \mathbf{M}) \rightarrow (\mathrm{H},\ -\mathrm{E},\ \det(\mathbf{M}) \cdot \mathbf{M}^{-1})$. Applying this transformation, we see the eigenmodes transform TE$\leftrightarrows$TM, and for a ferrite, duality leads to $\epsilon \leftrightarrows \mu$. Therefore, as the biased ferrite has a simple TM mode and nontrivial TE mode, by duality, a gyroelectric medium has a simple TE mode with dispersion $k^2 = \delta(\omega_n/c)^2$ and nontrivial TM mode with dispersion $k^2 = \epsilon_{\mathrm{eff}}\, \mu_r (\omega_n/c)^2$, where $\epsilon_{\mathrm{eff}} = (\kappa^2 - \chi^2)/\kappa$. By duality, the TM-SPP dispersion equation for the interface with an electric opaque medium with negative permittivity ε_s is $\alpha_s/\epsilon_s + \alpha_p/\epsilon_{\mathrm{eff}} = \chi k_{\mathrm{spp}}/(\kappa \epsilon_{\mathrm{eff}})$, where $\alpha_s = k_0 \sqrt{(k_{\mathrm{spp}}/k_0)^2 - \epsilon_s}$ and $\alpha_p = k_0 \sqrt{(k_{\mathrm{spp}}/k_0)^2 - \epsilon_{\mathrm{eff}}}$. For a ferrite, we will take [8]

$$\kappa = 1 - \frac{\omega_0 \omega_m}{\omega^2 - \omega_0^2} \quad \chi = \frac{\omega \omega_m}{(\omega^2 - \omega_0^2)} \quad \delta = 1 \tag{5}$$

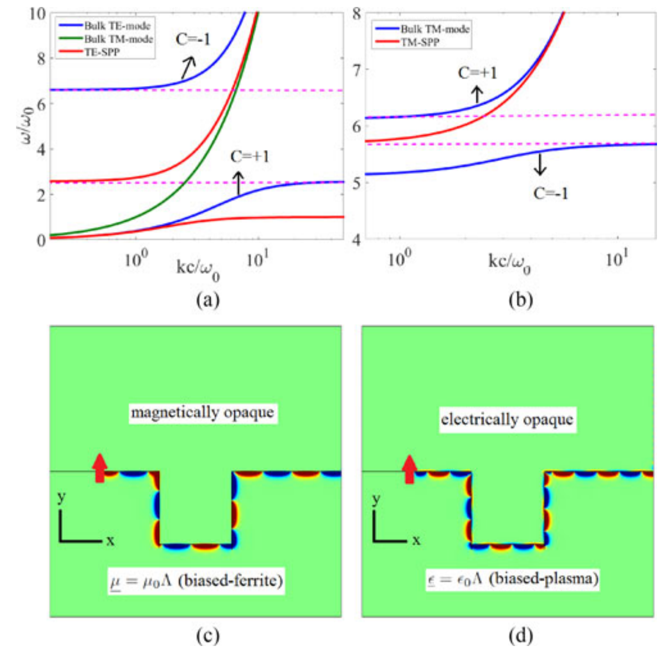

Fig. 1. (a) Bulk TE- and TM-mode dispersion and frequency gap of a biased ferrite with $\omega_0/2\pi = 1.73$ GHz and $\omega_m/2\pi = 9.7$ GHz and the TE-SPP mode dispersion. (b) TM-bulk mode dispersion and frequency gap of a biased plasma and the TM-SPP line for $\omega_0/(2\pi) = 1.73$ THz, $\omega_p/(2\pi) = 9.7$ THz (the opaque medium is silver). Dashed lines indicate the gaps. (c) One-way TE-SPP at the interface of biased ferrite and a medium with large negative μ_s at $f = 10$ GHz. (d) One-way TM-SPP at the interface of a biased plasma and a medium with large negative ϵ_s at $f = 10$ THz.

where $\omega_0 = \mu_0 \Gamma H_0$ is the Larmor frequency, $\omega_m = \mu_0 \Gamma M_s$, and where Γ, H_0, and M_s are the gyromagnetic ratio, biasing magnetic field, and saturation magnetization, respectively. For the gyroelectric material, we assume [9]

$$\kappa = 1 - \frac{\omega_p^2}{\omega^2 - \omega_0^2} \quad \chi = \frac{-\omega_0 \omega_p^2}{\omega\,(\omega^2 - \omega_0^2)} \quad \delta = 1 - \frac{\omega_p^2}{\omega^2} \tag{6}$$

where $\omega_0 = (q_e/m_e)B_z$ is the cyclotron frequency, $\omega_p^2 = N_e q_e^2/\varepsilon_0 m_e$ is the plasma frequency, B_z is the bias field, N_e is the free electron density, and q_e and m_e are the electron charge and mass, respectively.

The key point of interest here is that the gyromagnetic material and, by duality, the gyroelectric material have bulk bands with a band-gap. Indeed, Fig. 1(a) shows that the bulk TE mode of the gyromagnetic medium has a frequency gap (the bulk TM mode is gapless), with the TE-SPP dispersion line crossing the gap. If we excite the TE mode at the interface of a magnetic opaque material and biased ferrite at a frequency in the band-gap, there is no radiation into the half-spaces while we have a surface wave at the interface. Due to positive group velocity of this SPP (based on the slope of the band, since $v_g = \partial\omega/\partial k_{\mathrm{spp}} > 0$), surface wave propagation is only allowed in the positive x-direction. That is, the mode is unidirectional and cannot be backscattered by two-dimensional (2-D) imperfections at the surface. This is shown in Fig. 1(c), where a 2-D source excites the interface mode, computed with COMSOL. Here, we restrict attention of 2-D discontinuities; three-dimisional (3-D) discontinuities can indeed scatter energy in other directions [17], but this is beyond the scope of this study.

By duality, for the gyroelectric medium interfaced with an electrically opaque medium, the TE mode is gapless, the TM mode has a gap, and the TM-SPP crosses the gap with positive slope, as previously considered [14], [16], [20], and is shown in Fig. 1(b). This results in a unidirectional surface wave that is protected from backscattering, as shown in Fig. 1(d). It should be emphasized that the dispersion curves for the gyromagnetic and gyroelectric cases, Fig. 1(a) and (b), differ only because of the different values (κ, χ, δ) for each material. Furthermore, in each case we simply need an opaque medium as the second medium; we only consider $\mu_s < 0$ and $\varepsilon_s < 0$ for the gyromagnetic and gyroelectric cases, respectively, for convenience since it allows duality to be applied to the entire system.

Flipping the space vertically, $y \to -y$, where y is the vertical coordinate, results in the SPP propagating in the opposite direction (as also occurs by changing the direction of the bias field). This can be easily understood from the derivation of (3), which assumed $e^{-\alpha_s y}$ and $e^{\alpha_f y}$ in the upper and lower half-spaces, respectively. Applying $y \to -y$ leads to SPP field variation $e^{\alpha_s y}$ and $e^{-\alpha_f y}$, which changes the sign of the right side of (3).

B. Berry Curvature and Chern Number

Topology is concerned with quantities that are preserved under continuous deformations; a common example is that a torus and a coffee cup are topologically equivalent [6]. Different topologies can be mathematically characterized by integers called topological invariants. For the above example, the topological invariant is its genus, which corresponds to the number of holes within a closed surface (both a torus and a coffee cup have one hole). Topologies for material systems in photonics are defined on the dispersion bands in reciprocal (wave-vector) space. The topological invariant of a 2-D dispersion band is the Chern number, a quantity that characterizes the quantized collective behavior of the photonic states. These states will be persistent in the presence of perturbations that do not change the topologically of the structure (in the mechanical analog, those that do not open or close a hole in the material).

For a general bianisotropic medium, sourceless Maxwell's equation can be written as [16] $\hat{H}_{cl} \cdot \mathbf{f} = \omega \mathbf{f}$, where $\hat{H}_{cl} = \mathbf{M}^{-1}\hat{N}$,

$$\hat{N} = \begin{pmatrix} 0 & -\mathbf{k} \times \mathbf{I}_{3\times 3} \\ \mathbf{k} \times \mathbf{I}_{3\times 3} & 0 \end{pmatrix} \ \mathbf{f} = \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix}.$$

This compact form of Maxwell's equation has the same form as the Schrödinger equation, $\hat{H}|\Psi_n >= \hbar\omega_n|\Psi_n >$ with $\hbar = 1$. Because of this similarity between Maxwell's equations and the Schrödinger equation, it is straightforward to extend a concept originally developed for electronic states, the Berry vector potential, to photonic states [19].

Assuming the inner product of eigenmodes as $\langle \mathbf{f}_n | \mathbf{f}_m \rangle = \frac{1}{2}\mathbf{f}_n^*[\partial(\omega \mathbf{M}(\omega))/\partial\omega]\mathbf{f}_m$, the Berry vector potential (here, a $\mathbf{k}$-space analog of magnetic vector potential) is $\mathbf{A}_n = i\langle \mathbf{f}_n | \nabla_{\mathbf{k}} \mathbf{f}_n \rangle$, where $\nabla_{\mathbf{k}}$ operates over parameter space $\mathbf{k} = (k_x,\, k_y,\, k_z)$. The Berry curvature (a $\mathbf{k}$-space analog of magnetic flux density) is $\mathbf{F}_n = \nabla \times \mathbf{A}_n$. In parameter space, the flux integral over a closed manifold of the Berry curvature is quantized in units of 2π, indicating the number of Berry monopoles (degeneracies) within the surface

$$C_n = \frac{1}{2\pi} \oint_S \mathbf{F}_n \cdot d\mathbf{S} \tag{7}$$

where C_n is an integer for the nth state known as the Chern number, and S is a surface in parameter space (here, the $k_x - k_y$ plane, which can be mapped to the Riemann sphere [16]).

For the biased ferrite, the TE eigenmode is $\boldsymbol{f_n} = (\mathbf{E}\ \ \mathbf{H})^{\mathrm{T}} = (0, 0, \hat{\boldsymbol{z}} \quad \boldsymbol{\Lambda}^{-1} \cdot (\boldsymbol{k} \times \hat{\boldsymbol{z}})/\mu_0\omega_n)^{\mathrm{T}}$, and the Chern number has been obtained analytically using the method described in [16], resulting in $C = -1$ (upper band) and $C = +1$ (lower band), as indicated in Fig. 1(a). For the biased plasma in Fig. 1(b), $C = +1$ (upper band) and $C = -1$ (lower band) [17], [20]. By duality, the expressions for the Chern numbers are identical; the values differ due to different dispersive functions (κ, χ, δ) for the two materials. In general, the number of one-way SPP modes is equal to the difference of gap Chern numbers between the two mediums, where the gap Chern number $(C_{\mathrm{gap}} = \sum_i C_i)$ is the sum of the Chern numbers of all modes below the bandgap. For our particular case, $C_{\mathrm{gap}} = +1$, and so we have one unidirectional surface wave as shown in Fig. 1(c). By duality, the same statement applies to the biased plasma. It can be noted that when TR symmetry is unbroken (the nonbiased case), $\mathbf{F}_n(-\mathbf{k}) = -\mathbf{F}_n(\mathbf{k})$, and the integral of the Berry curvature will yield $C_n = 0$ and $C_{\mathrm{gap}} = 0$, such that no one-way SPP will propagate.

III. Plasmonic Directional Coupler

An important device that can benefit from having a unidirectional SPP is a directional coupler (DC). This can be implemented at GHz frequencies using either biased plasma or biased ferrites, or at THz frequencies using biased plasma. Consider a slab of biased plasma sandwiched between two slabs of an electrically opaque material (here we use $\epsilon_s = -20$, but any opaque medium can work). Fig. 2 shows a full-wave simulation (COMSOL) of the proposed THz plasmonic directional coupler. In Fig. 2(a), the source is located at the top interface (the input, Port 1) and is radiating in the frequency gap of the biased plasma. The metallic gate (coupling between top/bottom interface) is completely closed. At the input port, the SPP mode propagates toward the right and follows the interface to the bottom, continuing on toward the coupled port (Port 3). There is no SPP at the through port (Port 2). In Fig. 2(b), the gate is opened slightly so the SPP partially appears at the through port (2), but most of it is still travels to the coupled port (3). In Fig. 2(c), the spacing of the gate is increased, and most of the SPP energy appears at the through port (2), with a small fraction appearing at the coupled port. If we open the gate even more, as in Fig. 2(d), all of the SPP will go into the through port (2), and the input and coupled port are completely decoupled. As it is clear from Fig. 2(d), because of the one-way nature of the excited SPP, there is no reflection/diffraction at the site of the coupling gate, and the SPP passes the barrier without any backscattering toward the input port. There is never any power coupled to the isolation port (4), which is ideal. The amount of power coupled from input port to coupled and through ports can

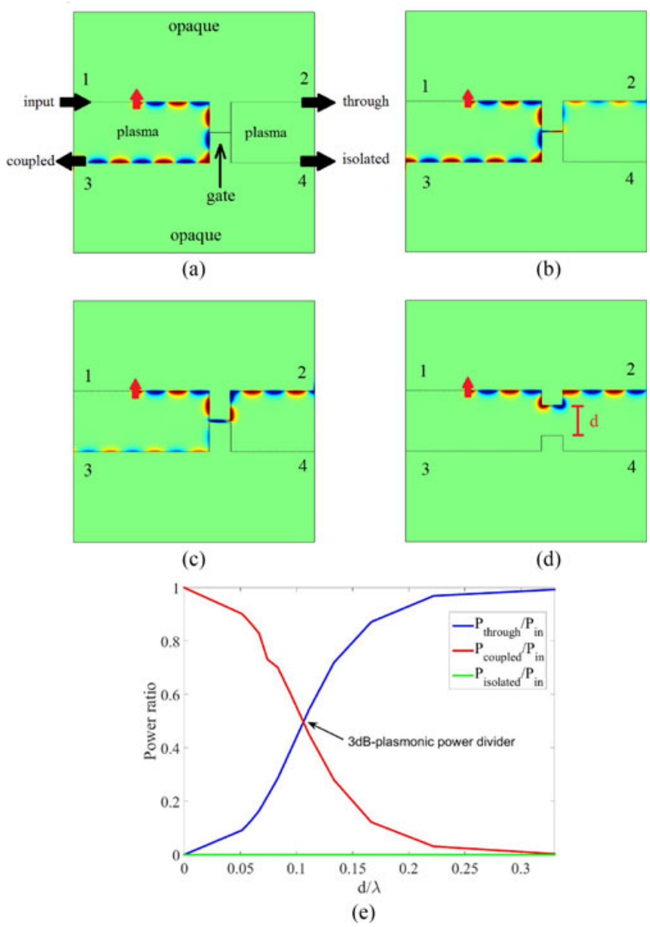

Fig. 2. Electric field distribution of TM mode SPP at different ports of the THz plasmonic directional coupler. (a) Coupling gate is completely closed: perfect coupling, perfect isolation. (b) Coupling gate is slightly open: partial coupling with most of the power at the coupled port, perfect isolation. (c) Coupling gate is open: partially coupling with most of the power at through port, perfect isolation. (d) Coupling gate is completely open: perfectly decoupled input and coupled ports, perfect isolation. (e) Power ratio at different ports for different values of gate opening. Biased plasma parameters are given in Fig. 1, electric opaque medium has $\epsilon_s = -20$, and the source is radiating at $f = 10$ THz.

be tuned by changing the spacing of the gate. Fig. 2(e) shows the coupled power from input port to the other ports. This device can be used as a plasmonic power divider due to the continuous control over the power appearing at the coupled and through ports.

Major issues with DCs are: 1) having ideal isolation at the isolated port; 2) bandwidth limitations due to the resonant nature of some conventional couplers; and 3) matching the loads and preventing power reflection back to the source. Due to the unidirectionality of the SPP, the coupler described above does not allow any power reflection back to the source as long as the source operates in the bulk material gap. The bandwidth of this coupler is determined by the bandwidth of the bulk material frequency gap, which can be tuned using the static biasing magnetic field of the plasma. There is no power in the isolated port, so there is no need for a perfectly matched load at the isolation port. Note that a waveguide coupler implemented using a photonic band-gap material has been presented in [22].

IV. Conclusion

The dispersion equation of the TM surface plasmon polariton at the interface of a biased gyromagnetic material and a magnetically opaque medium has been obtained, and it was shown that the dispersion of this surface mode crosses the frequency gap of the bulk material leading to a unidirectional surface mode topologically protected from backscattering. Duality with the gyroelectric case was discussed, and the Chern number, a topological invariant of the bulk material, has been obtained. A plasmonic directional coupler was proposed with several advantages over conventional couplers.

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