Line Waves at the Interface of Magneto-Electric Boundaries

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Abstract

Line waves (LWs) are exceptional electromagnetic (EM) modes found at the junctions of impedance surfaces, satisfying either electromagnetic duality or the parity-time symmetry. To date, the implementation of LWs has been limited primarily to employing electric impedance surfaces, and a magnetic media sustains the LW exhibiting backscattering-immune transportation. The entirely magnetic media ($\epsilon = 1$, and $\mu \neq 1$) supports TE-polarized surface magnon polaritons while we tailor the electric surface impedance to support TM-polarized surface waves. Remarkably, the envisioned line-wave waveguide emerges as a pseudospin-filtered channel, facilitating a uni-dimensional wave generated through the synergistic interplay of two surface waves possessing perpendicular polarizations. Our theoretical findings, corroborated by simulations, unveil a new type of polaritonic wave characterized by remarkably confined properties. This discovery holds promise for manipulating light on the nanoscale, opening avenues for the implementation of magneto-electric pseudospin-polarized waveguide.

Introduction

Spin waves are fundamental quasiparticles that depict the collective movement of magnetic moments within ordered systems (missing citation). These spin waves are capable of traversing materials, facilitating the transmission of a spin current. From the perspective of analogous quasiparticles, spin waves are referred to as magnons, representing collective spin lattice excitations similar to the phonon vibrations of the nuclear lattice (missing citation). Unlike traditional electrical currents, spin currents entail no charge transport, thereby eliminating Joule heating losses associated with electrical conduction (missing citation). Spin waves exhibit a broad spectrum of frequencies, ranging from gigahertz to several hundred terahertz (missing citation).

On the other hand, Surface magnon-polaritons are a variety of quasiparticle found in condensed matter physics, arising from the coupling between incident electromagnetic radiation and the magnetic dipole polarization in a solid’s surface layers (missing citation). Magnons, akin to plasmons and phonons, exhibit characteristics of polaritons, representing an oscillation in the magnetic component of the solid’s electromagnetic field, distinct from its electric component or mechanical vibrations in the atomic structure. Sometimes referred to as magnetic surface polaritons (MSPs), SMPs can be more readily manipulated by utilizing artificially engineered metamaterials, which derive their properties mainly from their designed internal structures rather than their overall physical composition (missing citation). Nonetheless, surface magnon-polaritons are also observable in various natural magnetic materials, including antiferromagnetic crystals, particularly at THz frequencies. By leveraging magnons, it becomes feasible to govern interactions between light and matter, particularly at Terahertz frequencies (missing citation).

Recently, both theoretical and experimental investigations, as cited in (Horsley & Hooper, 2014), have unveiled a novel electromagnetic mode capable of traveling along the interface line between two metasurfaces.
characterized by dual surface reactances, as evidenced by (Dia’aaldin & Sievenpiper, 2017; Bisharat & Sievenpiper, 2019; Kong et al., 2019; Xu et al., 2019; Singh, 2021; Davis et al., 2021; Xu et al., 2022; (missing citation); Xu et al., 2021; (missing citation). These waves, commonly referred to as "line waves," though also termed "one-dimensional waves," represent the one-dimensional counterpart of surface waves. They arise at discontinuities in surface reactance and/or resistance of low-dimensional materials such as metasurfaces or graphene, as discussed in (missing citation). Line waves constitute a rapidly developing area of research with promising potential for applications in fields such as sub-diffractive sensing, near-field imaging, and optical quantum computing. They possess unique properties including field enhancement, bandwidth, propagation-dependent polarization, robustness, and potential reconfigurability, making them an attractive option for various applications such as integrated photonics and optical sensing. Additionally, in our prior work, we proposed employing graphene-based technology for actively manipulating infrared line waves, detailed in (missing citation).

Here, we demonstrate that when surface magnon polaritons are introduced, a novel form of LWs can emerge, showcasing characteristics akin to conventional LWs, such as sustaining spin-momentum locked states. We delve into the dynamics of surface magnon polaritons propagation within a magnetic medium, deriving their dispersion characteristics within a slab structure. Moreover, we scrutinize the genesis of LWs along the magneto-electric interface within a planar waveguide. The propagation properties of proposed configurations, supporting unidirectional pseudospin states, are comprehensively analyzed. Furthermore, we introduce several single-layer waveguide designs tailored to guide LWs. Subsequently, we investigate the guidance of LWs within bilayer waveguides under diverse conditions, while delving deeply into the intricate realm of hybrid spin angular momentum carried by different designs of line-wave waveguides.

Results and discussion

Figure 1: A diagram illustrating suggested setup able where in the x-z plane, a magneto-electric junction supports a new kind of line wave.

In the illustrated schematic, Figure 1 highlights a configuration featuring an interface formed through connecting an inductive impedance surface to a magnetic slab within a 3-D Cartesian framework. The impedance surface is positioned in vacuum at $x \leq 0$ on the $x - y$ plane, where $x > 0$ denotes the magnetic media. It
is assumed that being electrically conductive (i.e., $\sigma_e \neq 0$, and $\sigma_m = 0$), the impedance surface is not magnetically conductive. Alternatively, the condition regarding the magnetic thin film is opposite (i.e., $\sigma_m \neq 0$, and $\sigma_e = 0$). The electric surface is characterized by an isotropic impedance boundary requirement (missing citation)

$$E_t = Z_s u_z \times H|z = 0$$

(1)

where the "t" subscript signifies the tangential component, and $u_z$ denotes a unit vector oriented along the z-axis. The electric impedance surface exhibiting an inductive response can be described as follows (Dia’aaldin & Sievenpiper, 2017)

$$Z_s = j\frac{\eta_0}{\zeta}, \text{ if } x < 0.$$  

(2)

In this scenario, $\zeta$ is a real parameter lacking dimensions, defined as $\zeta = |j\eta_0/Z_s|$. Moreover, $\eta_0$ denotes the intrinsic impedance of free space. The electric surface enables the propagation of a surface wave featuring TM polarization, contingent upon the reactance of impedance is inductive. The surface wave travels unattenuated along the y-axis, and experiences exponential decay in the z-direction with the defined propagation constant.

$$\beta_{TM} = \frac{\omega}{c} \sqrt{1 - \left(\frac{Z_s}{\eta_0}\right)^2}$$

(3)
Figure 2: Surface waves propagation constant at the frequency of 6THz for (a) the electric impedance surface, and (b) the magnetic media.

Figure 2(a) plots the dispersion characteristic of the TM-polarized surface wave guided through the inductive surface impedance showcasing a decrease in the confinement of surface waves as ζ increases. The confinement factor of surface wave at the frequency of 6THz spans < Real(β/K₀) for < ζ <. Besides the electric impedance surface, the magnetic film constitutes the uni-dimensional channel sustaining the line wave. Previous studies have explored the handling of surface waves in various scenarios, including cases involving surface plasmons, surface phonons, or their combination. However, as for LWs, situations exclusively involving magnetic materials facilitating the propagation of TE-polarized surface magnon polaritons has not been been examined. The EM parameters of the entirely magnetic media are conveniently specified in terms of three quantities: relative permeability εᵣ = 1, relative permittivity µᵣ ≥ 1, and magnetic loss tangent tan(δₘ). (missing citation); (missing citation). We examine the TE surface wave propagation within a finite-thickness magnetic slab featuring positive permeability, where the slab’s thickness is denoted as t, as depicted in Figure 2(b). The slab consists of an entirely magnetic material with the positive permittivity of ε = ε₀ and positive permeability of µ = µᵣ × µ₀. The upper and lower regions of the slab are free-space. Consequently, we derive the subsequent eigenvalue equation for the surface wave as follows

\[ (µᵣ × µ₀ × δ₀ - µ₀ × δ₁)^2 - (µ₁ × δ₀ + µ₀ × δ₁)^2 × \exp (-2 × δ₁ × T) \]

Figure 4(a) demonstrates the electric field distribution of the LW over a cross-sectional area of the waveguide. Akin to LWs at the interface of complementary metasurfaces with identical unit cell sizes, the proposed structure sustains asymmetric LWs. However, this issue can easily be addressed through employing a bilayer structure, as we will discuss in subsequent sections (missing citation); (missing citation). The vector-field distribution of LWs is illustrated in Figure 4(b). Evidently, the electric field is tangential to the TE surface and perpendicular to the TM surface. The resultant of surface waves vectors with perpendicular polarizations yields LWs with inclined polarization. On the other hand, the vector distribution of magnetic fields is opposite to that of electric fields. begin figure}[ht]
Spin waves, also known as collective motion of magnetic moments within magnetic media, represent fluctuations in spin that traverse the material akin to waves. These phenomena possess characteristic attributes like wavelength, frequency, phase, and propagation velocity, akin to traditional waves. The concept of a magnon, a quasiparticle, encapsulates the behavior of spin waves, particularly in ferromagnetic materials where it quantizes the wave’s propagation. The energy of a magnon correlates with its frequency, while its momentum corresponds to its wavevector. Spin waves can interact with various stimuli, including light and acoustic waves, and can be excited and observed through methods like microwave antenna. Furthermore, they find application in radio frequency regimes, such as microwave devices and wireless communication systems. Figure 3 illustrates the spin chain of a ferromagnetic material in an excited state, wherein each spin undergoes a deviation from its initial equilibrium orientation to accommodate a single spin-flip across the entire spin chain. Analogous to surface plasmon polaritons, surface magnon polaritons refer to electromagnetic waves that propagate at the interface between a magnetic media and an insulator. They signify a combination of oscillations of spin waves and electromagnetic waves (polaritons) in a dielectric media.
Spin-filtering characteristics in LWs supported at the junction of magneto-electric medias

Pseudospin-polarized waveguides suppressing backscattering was firstly introduced by Chen et al (missing citation). On the other hand, the theorem of pseudospin states justifies that line-wave waveguides implemented by complementary metasurfaces are pseudospin-polarized waveguides as well (missing citation). The exploration of these waveguides endowed with the distinctive capability to support unidirectional waves through magnetic medias has remained unexplored. We observe that magneto-electric LWs possess intrinsic spin-momentum entanglement properties, aligning with the behavior of evanescent waves. These line waves also showcase chiral-coupling characteristics when interacting with circularly polarized sources. Illustrated in Figure 8, a pair of magnetic and electric dipoles called "a spin source" can initiate unidirectional propagation along the interface of magneto-electric boundaries, directionally dependent on its handedness. The out of phase dipoles excite the pseudospin up state ($\varphi^+$) while in phase ones excite the pseudospin down state ($\varphi^-$).

Regarding the proposed structure, the inductive impedance surface, and the magnetic slab, generally speaking, exhibit symmetries $\epsilon(-x) = \alpha_1\mu(x)$, and $\mu(-x)\alpha_2 = \epsilon(x)$ due to their mirror pairing about the y-z plane (missing citation). Note that $\alpha_1$ and $\alpha_2$ are real parameters. The inherent symmetry of boundary inversion ensures that our line channel possesses a unique spin-momentum locking capability, making it resilient against reflections caused by specific structural perturbations. To showcase whether our waveguide satisfies mirror symmetries, a T-junction configuration, illustrated in Figure 7, is designed. The pseudospin up state, when stimulated at port 1, connects to port 2, and port 3. To be precise only the spin-up forward mode is permitted in the forward direction. Meanwhile, the alteration of boundary conditions along ports 4 obstructs the transfer from pseudospin-up state to pseudospin-down state. Consequently, the proposed
structure is a spin-filtered channel. When the pseudospin-up forward mode is excited, the LW cannot be reflected as long as the mirror reflection symmetries remain intact. Wave propagation in this waveguide is protected by mirror symmetries.

Planar magnetic waveguides sustaining coupled LWs

Figure 7(a) depicts the diagram of a bilayer magnetic waveguide, showcasing mirror symmetries around the x-y plane. A height of $h = \lambda_0/10$ is considered for the waveguide, where $\lambda_0$ is the working wavelength. In this setup, the distribution of inductive surface impedance along the y-z plane naturally aligns symmetrically. Consequently, maintaining this symmetry yields perfectly symmetric LWs, as evidenced in Figure 7(b). Moreover, the configuration couples two LWs, as illustrated in Figure 7(c), and their interaction gives rise to symmetric LWs. Furthermore, Figure 7(d) demonstrates a scenario where one magnetic surface is omitted, eliminating the structure’s mirror symmetry about the x-y plane. The lower layer of the waveguide sustains a line wave, while the upper and lower inductive surface impedance layers form a capacitive coupling, guiding an edge mode. Intriguingly, despite removing the magnetic medium, the mode symmetry remains intact, as depicted in Figure 7(e). Figure 7(f) clearly portrays a coupled mode facilitated by the proposed structure, where the symmetry between upper and lower modes differs.

Light exhibits two distinct forms of angular momentum: spin angular momentum and orbital angular momentum. These dynamic attributes not only differentiate light but also play a crucial role in its interactions with matter. Spin angular momentum arises when the electric field vector traces a helical path during propagation, while orbital angular momentum is associated with electromagnetic waves featuring an azimuthal phase dependence. For example, vortex beams carry orbital angular momentum proportional to their topological charge. Various light modes, such as evanescent waves and focused beams, possess transverse spin angular momentum perpendicular to the propagation axis, whereas circularly polarized plane waves in free space carry longitudinal spin angular momentum parallel to the propagation direction. The LW, distinct from others, exhibits decay of electromagnetic fields in two perpendicular directions to the propagation axis, resulting in six field components. While it shares characteristics with both TE and TM modes, it boasts a unique spin orientation, setting it apart. The determination of local spin density, measured in units of $\hbar$ per photon, is derived from a specific equation.
Here, $W$ denotes the localized energy density of the fields. Following the theorem of pseudospin states, the suggested waveguide facilitates hybrid modes. Since the parallel-plate waveguide supports coupled line waves, it is expected that this feature holds true for spin angular momentum as well. Figure 9(a) illustrates variations in electric field for coupled line waves, where each waveguide layer carries non-transverse spin angular momentum, coupled in-phase to the spin AM of the other layer. Alternatively, Figure 9(b) showcases that the spin AM of our proposed waveguide has an electric origin (i.e., $S = S_e$). This non-transverse spin angular momentum arises as the magnetic media supports the propagation of surface waves with TE polarization. Furthermore, since LWs are essentially pseudospin states, a similar behavior is expected regarding magnetic fields. Figure 9(c) illustrates variations in magnetic fields for coupled LWs, displaying the coupled spin AM. On the other hand, as depicted in Figure 9(d) demonstrates that this spin angular momentum also possesses the magnetic origin (i.e., $S = S_m$).

Figure 10(a) depicts a setup with a magnetic-electric-magnetic platform capable of sustaining coupled line modes. Additionally, it features a co-propagating surface wave guided by the inductive impedance surface as shown in Figure 10(b). In essence, the intrinsic spin angular momentum can typically be categorized into three types: the familiar longitudinal spin angular momentum aligned with momentum, the transverse spin angular momentum perpendicular to momentum, and the non-orthogonal/transverse type associated with LWs (Bisharat & Sievenpiper, 2018). Figure 10(c) illustrates the distribution of spin angular momentum density for a surface wave traveling along the $y$-axis, indicating a potential exponential decay in the $x$-direction. Due to the wave’s evanescent characteristics, an imaginary longitudinal component arises, inducing a rotation of EM fields within the $y$-$z$ plane. This rotation is characterized by a purely transverse spin angular momentum with an electric origin (denoted as $S = S_e$, and $S_m = 0$). It’s worth noting that this spin angular momentum depends on momentum but is independent of helicity. Figure 10(d) illustrates the spin angular momentum density of coupled line modes at various $\zeta$ values. For lower values of $\zeta$ both transverse and LW spin angular momentum are present, whereas greater $\zeta$ values lead to nearly pure transverse spin angular momentum. Consequently, manipulating the spin characteristics of LWs can be achieved by altering $\zeta$. 
Numerical Analysis

Full-wave EM simulations were conducted using ANSYS HFSS, a commercially available software based on the finite element method. The Driven-mode setup was employed to explore configurations excited by a source. In our computations, a 3D parallelepiped computational domain with a height of $\lambda_0/2$ along the z-axis was utilized, and two Wave Ports were positioned at the input and output of the waveguide to collect transmission data. HFSS Wave Ports require a consistent cross-sectional length at their connection point. Initially, HFSS calculates a 2D solution for the wave port, which is then used as the source for the 3D model. The process commences with solving the 2D fields on the port surface. The Eigenmode setup was utilized to examine dispersion relations, with the structure under investigation represented as two adjacent semi-infinite boundaries.

References


