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Nonreciprocal Time-Invariant Leaky Waves Enabled by Magnetized Plasma

Armin Ewert, *Graduate Student Member, IEEE*, and Daniel F. Sievenpiper, *Fellow, IEEE*

Abstract—This work demonstrates a passive time-invariant leaky-wave antenna exhibiting nonreciprocal radiation based on magnetized plasma in the Voigt configuration. The structure comprises a plasma layer biased by a magnetic field, interfaced with a dielectric substrate and air. Excited TM_0 surface waves propagate along the dielectric-air interface transition to radiative leaky-wave modes. Experimentally observed nonreciprocity includes an 8 dB gain asymmetry between transmission and reception that is reversible via magnetic field polarity inversion. Multiple frequency bands exhibit three distinct radiation mechanisms with nonreciprocal fast-wave leakage and a truly unidirectional leaky mode. These are predicted by the derived dispersion relation. Radiation patterns under magnetized plasma and unmagnetized plasma conditions confirm nonreciprocal transmission exclusively in magnetized states. Simulations closely match measurements and validate tunable operational frequency and nonreciprocal response through plasma density and magnetic bias control. This platform enables passive nonreciprocity without time modulation and offers applications in communications, radar/sensing systems, radar cross-section reduction, and RF front-end optimization.

Index Terms—antenna measurements, leaky wave antennas, nonreciprocal wave propagation, plasma waves, plasmons

I. INTRODUCTION

OVERCOMING the fundamental constraint of reciprocity in antennas unlocks transformative capabilities like distinct beam angles for transmission (TX) and reception (RX). The progressive coupling of guided wave energy to free space in leaky wave antennas results in frequency-dependent beam steering, commonly referred to as beam squint [1]. Radiation occurs when phase velocity of the waves within a waveguide structure exceed the speed of light and thereby become radiative (fast waves) [2]. Nonreciprocal LWAs, an emerging subclass, produce asymmetric radiation patterns challenge the Lorentz reciprocity theorem, a fundamental theorem in classical antenna design [3].

Nonreciprocity is typically engineered using gyrotropic materials like ferrites or plasmas, or via spatiotemporal modulation [4], [5]. Conventional approaches rely on bulky active components (isolators, circulators, amplifiers) for TX/RX isolation. Examples include nonreciprocal phased arrays using transistor-loaded phase shifters [6] or ferrite-loading for band decoupling [7]. Research into intrinsic nonreciprocity within

LWA structures has centered on gyromagnetic ferrites [8]–[12], metamaterials [13]–[16], and time modulation [17], [18]. This offers benefits like wide beam-scanning or bias tunability. Recent work includes a metasurface-based nonreciprocal horn antenna [19].

Magnetized plasmas present a compelling alternative to ferrites and metamaterials [4]. Although magnetized plasmas are well-established platforms for nonreciprocal surface waves (surface plasmon polaritons (SPPs) and surface magnetoplasmons (SMPs)) [20]–[25], their inherent slow-wave characteristics confine energy to the interface and suppress radiation [26]. While researchers have examined the topology of potential leaky modes [27] and analyzed a so-called ‘truly unidirectional’ leaky waves in layered magnetized plasma structure [28], no study has yet developed a functional magnetized plasma leaky-wave antenna with complete performance characterization. There remains a critical gap in practical implementation of full antenna metrics such as feed integration, radiation patterns, gain measurements, axial ratio, and efficiency analysis.

In this study we present, to our knowledge, the first dedicated antenna perspective on nonreciprocal leaky waves using capacitively coupled cold magnetized plasma. Our core novelty lies in exploiting the synergy between plasma tunability and magnetic nonreciprocity to intrinsically break Lorentz reciprocity within the radiating structure and enable unidirectional radiation. The derived dispersion relation for the proposed structure predicts multiple nonreciprocal leaky modes. These modes are validated by computational and experimental analysis. We demonstrate clear unidirectional radiation patterns and quantify the nonreciprocity through gain difference. Key experimental results include a measured gain exceeding 10 dB with a significant 8 dB gain difference at 5 GHz. We further provide a comparative analysis against ferrite and metamaterial-based nonreciprocal LWAs.

The plasma LWA offers distinct advantages over ferrites: dynamic on/off capability via plasma generation and high tunability of plasma frequency and electron cyclotron frequency for band shifting. Plasma generation introduces complexity absent in passive ferrites, but the benefits of dynamic control and frequency agility offer a strong alternative.

These unique characteristics enable applications like distinct beam angles for communication systems, which can achieve inherent isolation by using differently oriented transmit and receive beams. By leveraging intrinsic unidirectionality, RF front-ends could be simplified by eliminating circuitry for transmit-only nodes. Furthermore, these nonreciprocal LWAs offer reduced mutual coupling with adjacent antennas and

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facilitate active Radar Cross-Section (RCS) optimization. This study focuses on the microwave regime, but the fundamental physics supports scalability to all frequencies including THz and optical frequencies.

Section II describes the theory of cold magnetized plasmas and derives the dispersion relation of the electromagnetic structure under investigation. Section III focuses on the computational methodology and experimental apparatus, including the plasma source and measurement techniques. Section IV presents the radiation patterns, gain analysis, electric field distributions, and comparative discussion. Conclusions and future directions are outlined in Section V and supplementary data are provided in the Appendix (Section A).

II. THEORY

A. Capacitively Coupled Cold Magnetized Plasma

Cold plasmas for microwave applications are typically generated through low-pressure gas discharges (< 10 Torr) using inductive or capacitive coupling. These discharges yield electron densities n_e of $10^{16} - 10^{19} \text{ m}^{-3}$ and electron temperatures of $1 - 10 \text{ eV}$ that are significantly higher than ion temperatures leading to an ionization degree below 10^{-4} [29], [30]. The mass difference between electrons and ions justifies treating ions as a stationary neutralizing background, while the neutral gas exhibits relative permittivity $\varepsilon_r \approx 1$.

Wave-plasma interactions are governed by the complex conductivity $\sigma \propto n_e/(\nu_c + i\omega)$, where ν_c is the electron collision frequency and ω the angular frequency of the wave [31]. For GHz-range waves in low-pressure plasmas (where $\omega \gg \nu_c$ consistently holds), three approximations apply: (1), ion motion is negligible due to inertia at microwave frequencies. (2), collisional damping ν_c is omitted since electron inertia dominates behavior. (3), conductivity effects are excluded to isolate the dielectric response from electron displacement currents. These simplifications focus analysis on electron dynamics most relevant to microwave systems. Uniformity of the plasma in space and time is also assumed for kHz–MHz discharge frequencies because they are orders of magnitude below GHz excitations [31].

The electron plasma frequency $\omega_p = (n_e e^2 / m_e \varepsilon_0)^{1/2}$ is central to EM wave interactions, where e is the electron charge, m_e is the electron mass, and ε_0 is the permittivity of free space. For $\omega < \omega_p$, the electrons oscillate synchronously with incident fields by which a charge separation is induced that screens the plasma interior. The wave cannot propagate through the plasma and is reflected and absorbed. When $\omega > \omega_p$, the electron inertia is too large and prevents effective screen. The wave propagates through the plasma similar to a dielectric [29].

Applying a static magnetic field B_0 fundamentally changes how electrons in a plasma react to electromagnetic waves. Due to the Lorentz force the electrons gyrate around the magnetic field lines. This cyclotron motion happens at the electron cyclotron frequency $\omega_c = eB_0/m_e$, which scales proportionally with the field strength. Crucially, because magnetic fields break time-reversal symmetry, the plasma's response to waves can become nonreciprocal. This means the phase

shift and attenuation a wave experiences depend heavily on the direction of propagation relative to the magnetic field [32]. The magnetic field turns the plasma into a gyrotropic medium. Instead of having a simple scalar permittivity ε_p , the permittivity becomes a tensor with significant off-diagonal terms. These off-diagonal components are the mathematical signature of the anisotropy caused by the electrons' forced gyration. For the simplified case of a collisionless plasma, biased with B_0 aligned along the y -axis, the permittivity tensor takes the form [33]:

$$\underline{\varepsilon}_p = \begin{bmatrix} \varepsilon_t & 0 & -i\varepsilon_g \\ 0 & \varepsilon_a & 0 \\ i\varepsilon_g & 0 & \varepsilon_t \end{bmatrix} \quad (1)$$

where

$$\varepsilon_t = 1 - \frac{\omega_p^2}{\omega^2 - \omega_c^2}, \quad \varepsilon_a = 1 - \frac{\omega_p^2}{\omega^2}, \quad \varepsilon_g = \frac{\omega_c \omega_p^2}{\omega(\omega_c^2 - \omega^2)}$$

The magnetization-independent tensor component ε_a is described by the Drude model, while the magnetization-dependent diagonal term ε_t is modeled using the Drude-Lorentz formalism exhibiting an additional resonance [34].

The off-diagonal term ε_g in Eqn. 1 is responsible for the nonreciprocal electromagnetic response of the plasma. It couples orthogonal electric field components and introduces a directional asymmetry in the interaction between electromagnetic waves and the electron motion. As a result, waves traveling along the interface experience different phase velocities and attenuation depending on their propagation direction relative to the static magnetic field. This mechanism originates from the Lorentz-force driven electron gyration and represents the fundamental source of nonreciprocity in magnetized plasmas [32]. Such direction-dependent propagation properties are particularly attractive for microwave systems, since they enable devices that support preferential wave transport or radiation in a single direction. Examples include nonreciprocal radiating structures [28], isolating components [5], and directional surface-wave structures [25] that can operate without ferrite materials or time-modulated circuits.

In magnetized plasmas under Voigt configuration, electromagnetic wave propagation exhibits distinct cutoff and resonance frequencies for both bulk modes and surface waves. The extraordinary (X) mode, characterized by TM-like polarization, has two branches. Its lower branch experiences cutoff at the left-handed circularly polarized frequency $\omega_{\text{LCP}} = \frac{1}{2}(-\omega_c + \sqrt{\omega_c^2 + 4\omega_p^2})$, where the Voigt permittivity $\varepsilon_V = (\varepsilon_t^2 - \varepsilon_g^2)/\varepsilon_t$ vanishes [24]. This branch resonates at the upper hybrid frequency $\omega_{\text{uh}} = \sqrt{\omega_p^2 + \omega_c^2}$ due to divergence in ε_V . The upper branch cuts off at $\omega_{\text{RCP}} = \frac{1}{2}(\omega_c + \sqrt{\omega_c^2 + 4\omega_p^2})$ without resonant behavior [33].

Surface magnetoplasmons reveal strong nonreciprocity with directional resonances at $\omega_- = 1/2(-\omega_c + (2\omega_p^2 + \omega_c^2)^{1/2})$ and $\omega_+ = 1/2(\omega_c + (2\omega_p^2 + \omega_c^2)^{1/2})$ for counter-propagating waves. Their bandgap scales linearly with ω_c [35]. Backward waves where the group velocity turns negative have been observed in isotropic plasmas [36] and magnetized plasma below the

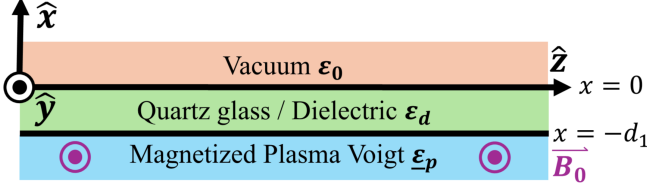


Fig. 1. System geometry in the $x - z$ plane: a homogeneous magnetized plasma occupies $x < -d_1$ with $B_0 \parallel \hat{y}$ (Voigt configuration). An isotropic dielectric layer (ϵ_d , thickness d_1) is terminated by a semi-infinite vacuum.

LCP cutoff ($\epsilon_V < 0$) [37]. These waves exhibit antiparallel alignment of the Poynting vector $\mathbf{S}$ and wave vector $\mathbf{k}$ [38], [39]. While this does not have an impact on causality, negative group velocity enables phenomena such as negative refraction [40].

B. Dispersion relation

The electromagnetic structure, comprising materials with contrasting permittivities aligned along the x -axis, is illustrated in Fig. 1. TM-mode propagation with harmonic time dependence ($e^{-i\omega t}$) and uniform progression along z ($e^{ik_z z}$) are assumed. Within the dielectric layer, fields oscillate or decay in the x -direction. In the semi-infinite magnetized plasma and air regions the wave is exponentially decaying in x . These principles apply equally to solid-state plasmas.

$$H_y = \begin{cases} H_{vy} e^{-\alpha_v x}, & x \geq 0 \\ A_d \cos(k_d x) + B_d \sin(k_d x), & -d_1 \leq x < 0 \\ H_{py} e^{\alpha_p x}, & x < -d_1 \end{cases} \quad (2)$$

where

$$\alpha_v = \sqrt{k_z^2 - \frac{\omega^2}{c^2}}, \quad k_d = \sqrt{\frac{\omega^2}{c^2} \epsilon_d - k_z^2}, \quad \alpha_p = \sqrt{k_z^2 - \frac{\omega^2}{c^2} \epsilon_V} \quad (3)$$

The quantities in Eqn. 3 correspond to the transverse wavenumber components in each region of the structure. In general, the wave vector can be written as $\mathbf{k} = k_x \hat{x} + k_z \hat{z}$, where k_z determines the phase progression along the interface and k_x describes the field variation normal to it.

For bound surface-wave solutions (slow waves), the propagation constant satisfies $|k_z| > \omega/c$. In this case the transverse wavenumber in the surrounding vacuum region becomes purely imaginary, $k_x = i\alpha_v$, which results in an exponential decay of the fields away from the interface. Such solutions therefore correspond to non-radiating surface waves confined to the plasma-dielectric interface.

Leaky-wave solutions occur when the propagation constant falls inside the vacuum light cone ($|k_z| < \omega/c$). Under this condition the transverse wavenumber becomes real, $k_x = \sqrt{\omega^2/c^2 - k_z^2}$, allowing the fields to propagate into the air region. These modes therefore radiate energy away from the interface and form the physical basis of leaky-wave antennas.

Consequently, the character of a solution can be identified from the combination of k_z and k_x : slow bound waves exhibit

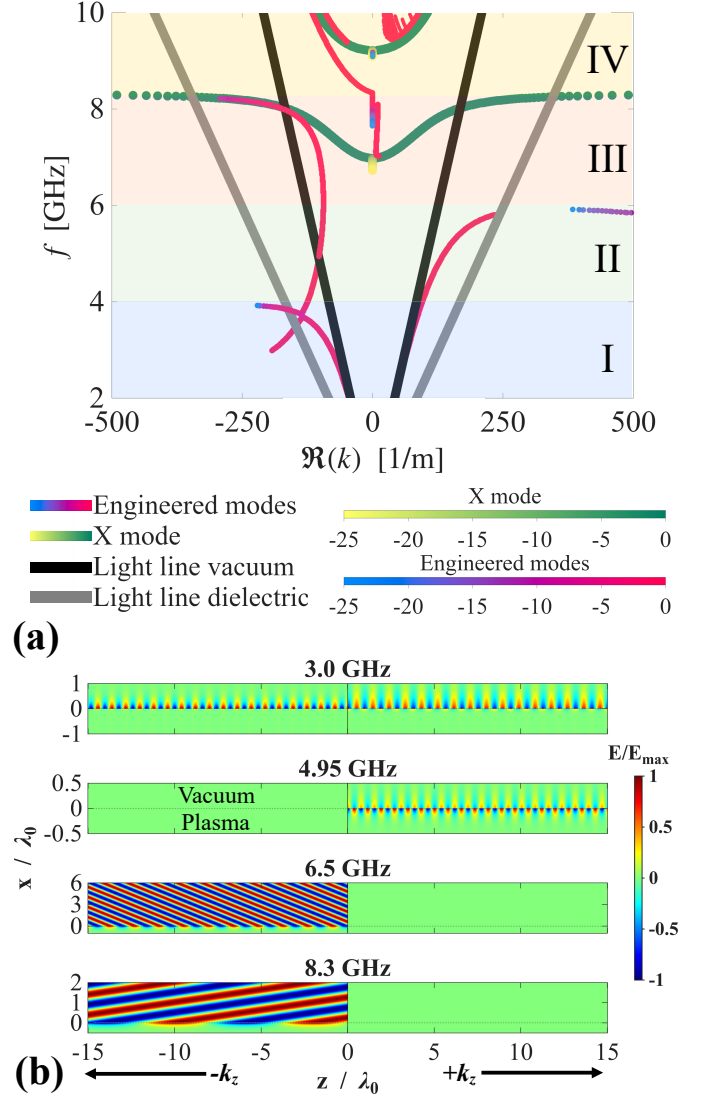


Fig. 2. (a) Dispersion relation evaluated numerically by Eqn. 4 using $\omega_p = 2\pi \times 8.1$ GHz ($\hat{=} n_e = 8 \times 10^{17} \text{ m}^{-3}$), $\omega_c = 0.28\omega_p = 2\pi \times 2.24$ GHz ($\hat{=} B_0 = 80$ mT), $\nu_c = 0.02\omega_p = 1$ GHz and dielectric constant 3.8 with thickness $d_1 = 0.01\lambda_p = 0.5$ mm, where λ_p is defined as the wavelength at the plasma frequency. Extraordinary (X) modes appear in green-yellow hues, while engineered modes use a blue-red scheme. Both color maps indicate the magnitude of the imaginary part of k_z which is proportional to radiation loss. Vacuum and dielectric light lines are shown in black and gray, respectively. (b) Electric field distributions in the xz -plane obtained from the dispersion relation at selected frequencies, illustrating unidirectional and bidirectional surface waves as well as nonreciprocal leaky modes. For $z > 0$ the propagation uses the positive wave number, while for $z < 0$ the negative wave number is used. The wave number is obtained from the dispersion relation and has the same magnitude on both sides.

real k_z and imaginary k_x , whereas radiating leaky waves exhibit real k_z and real k_x in the air region.

The field amplitudes H_{vy} , A_d , B_d , and H_{py} are the unknown coefficients. From Maxwell's equations, the expressions for the transverse field component E_x and tangential field E_z are derived. Electromagnetic boundary conditions of tangential components E_z and H_y at material interfaces generate four linear equations. The TM eigenmodes of the structure are obtained by finding the roots of the resulting

4×4 matrix determinant.

$$\begin{pmatrix} -1 & \cos(k_d d_1) & \sin(k_d d_1) & 0 \\ \gamma_v & -\gamma_d \sin(k_d d_1) & \gamma_d \cos(k_d d_1) & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & -\gamma_d & \gamma_p \end{pmatrix} \begin{pmatrix} H_{vy} \\ A_d \\ B_d \\ H_{py} \end{pmatrix} = 0 \quad (4)$$

where

$$\gamma_v = \frac{i\alpha_v}{\omega\epsilon_0}, \quad \gamma_d = \frac{ik_d}{\omega\epsilon_0\epsilon_d}, \quad \gamma_p = \frac{k_z\alpha_p + \omega^2\epsilon_0\mu_0\epsilon_g}{i\omega\epsilon_0\alpha_p\epsilon_g - ik_z\omega\epsilon_0\epsilon_t}$$

The numerically evaluated dispersion is shown in Fig. 2. It highlights the role of the imaginary component of the wave vector k_z , which represents the loss. Regions in red signify near-lossless surface wave propagation, whereas blue regions denote high attenuation and spatial decay. This imaginary part effectively quantifies mode localization at the interface.

Below 4 GHz, surface wave branches exist for both propagation directions. The different wave numbers for positive and negative k_z lead to nonreciprocal behavior. In the field plot, this appears as different spatial periods of the electric field at 3.0 GHz.

This asymmetry becomes more pronounced above 4 GHz as the lower branch detaches from the vacuum light line and approaches its resonance at ω_- , surface wave propagation from 4 – 6 GHz becomes restricted exclusively to the positive k_z direction, with the corresponding branch approaching resonance at ω_+ . At 4.95 GHz, the electric field propagates only in the positive direction and penetrates further into the plasma than at lower frequencies.

Another mode appears exclusively for negative k_z : it crosses the dielectric light line at 3.5 GHz with negative group velocity before merging with the lower X-mode branch. This mode implies strong nonreciprocal radiation as it exists within the vacuum light cone. This mode corresponds to a backward wave in the region up to approximately 6.5 GHz [8]. The electric field at 6.5 GHz exhibits leaky behavior, and the field distribution indicates a backward wave.

Above the upper hybrid frequency, a truly nonreciprocal leaky mode emerges which radiates only for negative k_z . This mode, which was studied theoretically in [28], merges into the upper branch of the X mode. Analysis of k_z shows that surface waves exhibit small imaginary components in the slow-wave region, thereby suppressing radiation. The electric field plot at 8.3 GHz confirms this behavior, showing a wave that leaks into the vacuum above. Both X-mode branches and the broadside-engineered modes ($k_z = 0$) originate from high-loss regimes. Similarly, the backward wave experiences radiative loss as it approaches the lower X-mode branch.

The dispersion relation in region I (2 – 4 GHz) predicts asymmetric surface wave propagation due to different wave numbers. In region II, surface waves emerge directionally: for positive k_z , the branch decouples from the vacuum light line, mirroring behavior in the lower region. Conversely, negative k_z waves enter the dielectric and vacuum light cones exhibiting fast wave radiation. This yields direction-dependent beam angles due to distinct wavenumbers and thus asymmetric radiation. The detaching branches in regions I and II exhibit

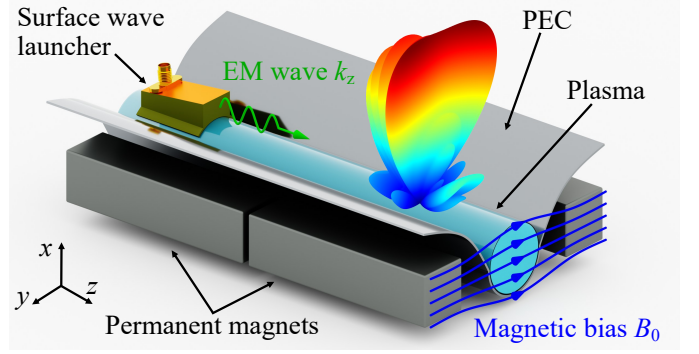


Fig. 3. Setup for computational and experimental analysis: a surface wave launcher is located on a dielectric cylinder with radius 32.5 mm, thickness 0.5 mm and dielectric constant 3.8. The plasma is enclosed by the cylinder. A PEC sheet is wrapped tightly around the lower half of the dielectric column and flares out in the upper half. Permanent magnets provide a uniform magnetic field in the direction perpendicular to the excited wave k_z . The wave is leaking along the surface in the $x - z$ -plane.

phase velocities below the speed of light, which inhibits natural radiation. However, under imperfect feeding conditions, reflections and scattering can interact with the magnetized plasma's direction-dependent surface impedance to give rise to nonreciprocal radiation. Region III permits only negative k_z radiation, as the backward wave extends to the lower branch of the X mode. Similarly, radiation in region IV occurs solely for negative k_z .

III. SETUP

The computational and experimental setup are shown in Fig. 3. Both configurations align closely to allow direct comparison of results. The primary distinction lies in the experimental use of permanent magnets, whereas simulations implement the modified permittivity tensor (Eqn. 1). A PEC layer positioned between the plasma column and the nickel-coated magnets suppresses reflections of the magnets. This confinement ensures maximum energy transfer in the desired direction ($+x$) and thereby increases aperture size to increase gain.

Electromagnetic waves couple into a dielectric structure ($\epsilon_r > 1$) through a parallel-plate waveguide bounded by PEC layers on the top and bottom. This waveguide operates in the dominant TEM mode and couples the energy into surface and leaky modes. A coaxial input connector couples waves from the excitation source into the waveguide modes of the structure. The coupler is located in the air at the interface to the dielectric as it is experimentally challenging to place it inside the plasma. While this precludes direct excitation at the three-material interface, it represents the closest feasible approach.

The derived dispersion relation (Fig. 2) assumes pure y -direction magnetization. Practical deviations arise due to unavoidable minor magnetization components in other directions. Wave propagation experiences ideal magnetization only along the one-dimensional line perfectly orthogonal to both the bias field ($\hat{y}$) and the transverse E-field E_x of the wave. At angles diverging from this cylinder axis, the wave's transverse magnetic field component experiences reduced y -bias

and non-interacting x -bias components. As a consequence, effective magnetization diminishes radially.

A. Computational

The electromagnetic simulations were conducted with the finite element solver Ansys HFSS. The surface wave launcher consists of a dielectric block ($\epsilon_r = 3$) with Perfect Electric Conductor (PEC) boundaries on the top and bottom surfaces and Perfect Magnetic Conductor (PMC) boundaries on the lateral faces. These conditions enforce TEM mode propagation that transforms into TM_0 in the z direction. Wave excitation occurs through a port positioned opposite the radiation direction, with field monitors confirming a pure TM_0 mode profile. Additional simulations show that of the power accepted into the structure, more than 90% of the power is carried by the TM_0 mode, while the TEM and TE modes together account for less than 10% over the whole analyzed bandwidth. This indicates high modal purity within the structure, confirming that the reported nonreciprocal behavior is dominated by the intended TM_0 mode, irrespective of the overall coupling efficiency from the input port. To verify the dispersion relation and visualize the nonreciprocity within a single field plot, a Hertzian dipole oriented along the x -axis is employed in place of the surface wave launcher. Positioned at the vacuum-dielectric interface, this dipole excites a vertically polarized electric field in the $y-z$ plane, which subsequently couples to the TM_0 mode.

Radiation boundaries enclose the entire structure to enable far-field computation. The plasma is modeled as a spatially and temporally uniform dispersive medium defined by its gyrotropic permittivity tensor (Eqn. 1). To address HFSS limitations in handling radiation boundaries adjacent to dispersive media, a 0.1 mm vacuum layer is introduced between the plasma cylinder bases and radiation domain. A PEC sheet replaces the physical magnet assembly, as it equivalently blocks field penetration. Material properties incorporate the collision frequency $\nu_c = 1$ GHz, which is retained for solution convergence despite its negligible electromagnetic influence $\nu_c \ll \omega_p$. The simulations excluded conductivity to conserve computational resources without sacrificing accuracy. To replicate experimental conditions, the numerical model was characterized via parametric frequency sweeps across a range of plasma densities and magnetic field strengths. Outputs include S -parameters, 3D radiation patterns, and electric field distributions.

B. Experimental

The experimental configuration uses a surface wave launcher fabricated from 3D-printed PLA ($\epsilon_r = 3$), with dimensions 18 mm (W) $\times$ 50 mm (L) $\times$ 13 mm (H). A flared profile matching the dielectric cylinder curvature optimizes directional wave propagation. Copper tape cladding on the top and bottom surfaces forms the parallel-plate waveguide boundaries, and additional copper shielding on the rear surface minimizes backward radiation. Parallel-plate waveguides provide efficient coupling from the TEM mode to the TM_0 mode [41]. This geometry couples waves from TEM into broadband

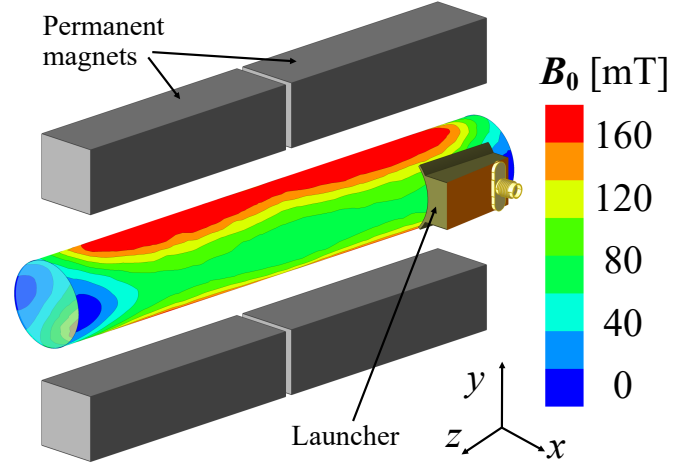


Fig. 4. Magnetic field magnitude of bias magnetic field B_0 computed with Ansys Maxwell.

TM_0 modes, though significant reflection losses occur due to impedance mismatch. The plasma is generated with an Ushio G20T10 germicidal lamp (quartz envelope: 32.5 mm OD, 0.5 mm wall thickness, 589 mm length) filled with argon gas and doped with mercury droplets. Tungsten filaments at both ends, heated by 10 V DC bias, enhance thermionic emission for ignition. A 37 kHz ballast supplies 7.5 W AC power for stable discharge operation. The mercury doping increases electron density to $10^{17} - 10^{18} \text{ m}^{-3}$ with a shift of the emission from argon distinct purple to light blue. The plasma density of fluorescent and UV bulbs has been extensively analyzed in recent studies [5], [42], [43]. Plasma uniformity is assumed except near quartz boundaries, where electron density declines sharply due to non-reflective wall interactions. Four N45-grade neodymium block magnets (100 mm $\times$ 25 mm $\times$ 25 mm, nickel-copper-nickel coating, 1900 N pull force) mounted in reinforced 3D-printed structures provide static y -direction bias. Hall probe measurements confirm computational field results that are illustrated in Fig. 4. The effective uniform magnetic flux density across the plasma column is 80 mT. It is known that magnetic bias increases plasma density [44]. A conformal PEC structure (3D-printed base with copper cladding) is placed beneath the plasma column to direct energy forward in the $+x$ -direction. Microwave absorber put on the surface wave launcher suppresses feed leakage and broadband reflections. Further, absorber is wrapped around the ends of the germicidal bulb to minimize surface wave diffraction.

Measurements initiate with argon-mercury plasma ignition in the germicidal bulb with the cathode bias set to 10 V DC. This operating point maximizes plasma density and yields the strongest nonreciprocity. The effective plasma frequency of 8.1 GHz adopted in the numerical model corresponds to this state of maximum achievable density. While the discharge exhibits a spatial density gradient where the density is lower near the tube walls, increasing the overall plasma density via the AC discharge and electrode bias consequently raises the density at these boundaries. Because the TM_0 surface waves are inherently localized at the plasma-dielectric interface, this

high-density state ensures that the effective interaction at the wall is sufficient to support the observed nonreciprocal phenomena, justifying the use of a value near the upper range of typical discharges. The discharge stabilizes for 30 minutes prior to data acquisition to mitigate density and temperature fluctuations arising from thermal equilibration of the experimental apparatus. The surface wave launcher connects directly to the anechoic chamber's calibrated reference port. A dual-polarized RCDLPHA2G18B horn antenna serves as the probe. It captures co- and cross-polarization simultaneously. To compensate for plasma temporal instabilities due to the AC power power supply, the vector network analyzer configuration uses a 10 kHz IF bandwidth with an average factor of 64. The frequency sweep is conducted from 2 – 10 GHz with 401 frequency points. Azimuthal plane scans acquire data at 1° angular increments. Given the inherent one-dimensional radiation pattern of leaky-wave antennas, measurements concentrate exclusively on the 90° elevation plane. Each full angular scan requires approximately one hour. Validation measurements repeated after initial completion confirm reproducible results. The experimental sequence successively captures three operational states: magnetized plasma conditions (with permanent magnets, acquiring both S_{21} and S_{12}), unmagnetized plasma (magnets removed), and a plasma-off baseline measurement. All acquired data are post-processed in MATLAB.

IV. RESULTS

A. Gain

The measured radiation patterns for S_{21} and S_{12} at 4.95, 6.3, 7 and 8.3 GHz are displayed in Fig. 5. These frequencies demonstrate remarkable phenomena according to the dispersion relation in Fig. 2. The radiation patterns at 4.95 and 6.3 GHz refer to region II of the dispersion relation. Region III is illustrated by the radiation pattern at 7 GHz and region IV at 8.3 GHz, respectively. The measurement of S_{21} and S_{12} refers to TX and RX, and can likewise be described as swapping the direction of the magnetic bias. A maximum nonreciprocity of 8 dB gain difference is observed at 4.95 GHz. While both patterns exhibit similar beam structure, S_{12} radiation shows a significantly attenuated main lobe without substantial side lobe alteration. Similar peak gains occur at 6.3 dB for S_{21} and S_{12} in the radiation pattern, though at distinct beam angles. At 7 GHz, opposing nonreciprocity of 4 dB is observed where the main lobe of S_{12} is weaker. Similarly, the asymmetry (3 dB) in the pattern at 8.3 GHz shows S_{12} attenuated. In either case, the other beam characteristics such as nulls and side lobes remain similar for TX and RX.

The maximum gain and realized gain versus frequency of S_{21} and S_{12} measurements is plotted in Fig. 6. Distinct nonreciprocal bands emerge: between 4 – 6.5 GHz, S_{21} gain exceeds S_{12} by up to 8 dB with a maximum of more than 10 dB gain with S_{21} plateauing near 6 dB. From 6.5 – 9 GHz, this asymmetry reverses with S_{21} gain exceeding S_{12} and peaking at 16 dB. The latter region exhibits a phase-offset-like progression between reciprocal states which indicates a dispersion-related wave delay. Gain calculations exclude mismatch loss, whereas realized gain accounts for it. The broadband surface wave launcher exhibits significant impedance

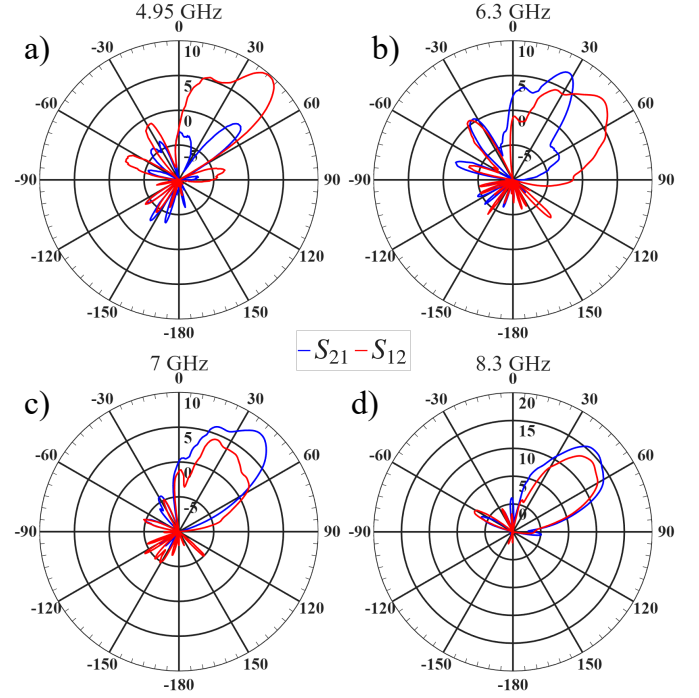


Fig. 5. Radiations pattern of S_{21} and S_{12} with excitation from $\theta = -90^\circ$ in the E-plane measured at a) 4.95, b) 6.3, c) 7, and d) 8.3 GHz.

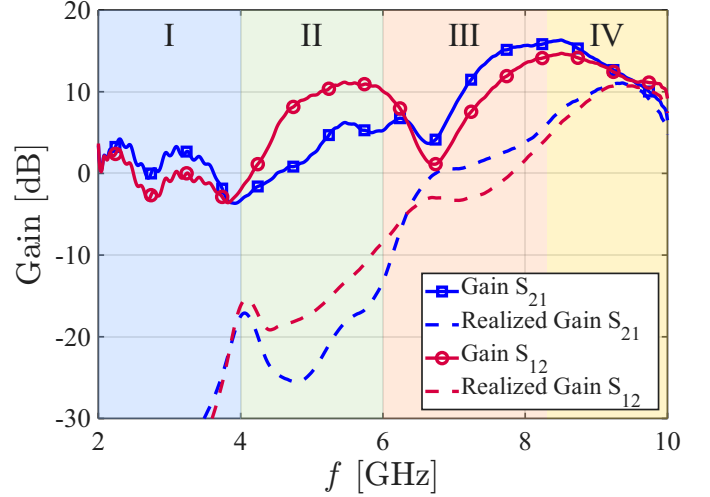


Fig. 6. Measured gain and realized gain of S_{21} and S_{12} versus frequency.

mismatch, particularly below 6 GHz, which is the primary source of the divergence between these two metrics. This mismatch arises from the transition between the coaxial input and the parallel-plate waveguide, where only a fraction of the incident power is coupled into the antenna structure. Despite this coupling limitation and the resulting lower realized gain at lower frequencies, the substantial measured gain of more than 10 dB indicates that the power which is accepted into the structure effectively transfers to the intended surface and leaky waves.

The difference between the measured gains from S_{21} and S_{12} is shown in orange in Fig. 7, and the purple curve represents the corresponding simulated results. Both traces exhibit

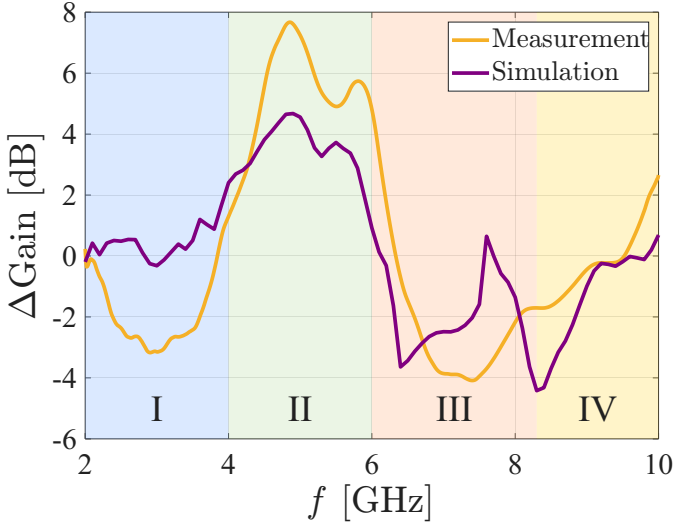


Fig. 7. Difference of gain from S_{21} and S_{12} with data acquired from measurements and simulation.

similar trends which indicates that the simulation reproduces the experimental behavior with reasonable accuracy. Some discrepancies are observed, that can be attributed to idealized assumptions in the simulation. Specifically, the model neglects impedance mismatch and permits arbitrarily small magnitudes. Further, it also assumes a perfectly uniform magnetic bias and plasma density. In comparison, around 7.5 GHz the gain difference nearly vanishes, but increases again sharply near 8.3 GHz. The derived and numerically evaluated dispersion relation presented in Fig. 2 aligns well with the simulated results and hence with experimental data, thus supporting the validity of the theoretical model. The first nonreciprocal band, occurring between 2 – 4 GHz, results from reflections and scattering as the wave couples into the electromagnetic structure. The inherent asymmetry of the plasma's surface impedance translates this coupling into a nonreciprocal radiation pattern. A second band of nonreciprocity (Region II) is observed between 4 – 6 GHz, originating from the same physical mechanism but manifesting for waves propagating in the opposite direction. The nonreciprocal response in region III from 6 – 7.5 GHz is attributed to the backward wave mode with the negative group velocity. Near 7.5 GHz, reciprocal radiation occurs, that is associated with the lower branch of the X-mode. Between 7.5 – 9 GHz (region IV), the nonreciprocal behavior is governed by a truly nonreciprocal mode that transitions into the upper branch of the X-mode. Above 9.5 GHz nonreciprocity arises due to modal asymmetry in wave vector space: although modes exist for both positive and negative wave vectors, their magnitudes differ slightly, which leads to observable nonreciprocal effects.

In Fig. 8, the simulated realized gain and radiation efficiency are presented. The realized gain is low at lower frequencies and increases toward higher frequencies, reflecting the frequency-dependent impedance mismatch in the parallel-plate launching structure. This confirms that while the overall system efficiency is limited by the feed transition at the lower end of the band, the radiating portion of the structure maintains

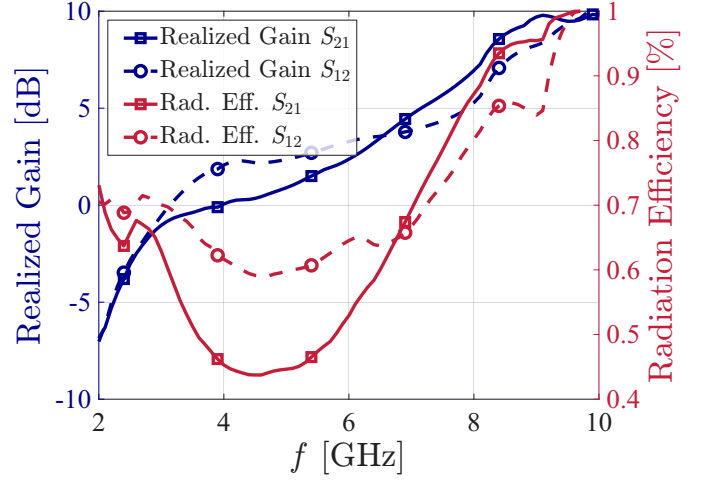


Fig. 8. Simulated realized gain and radiation efficiency.

high intrinsic gain and modal purity. The radiation efficiency shows differences between the S_{21} and S_{12} cases. It starts around 0.7 for both directions, but decreases near 5 GHz to approximately 0.6 and 0.4, respectively. At higher frequencies, the radiation efficiency approaches unity. In particular, the truly nonreciprocal mode around 8.3 GHz and above exhibits radiation efficiencies exceeding 0.9.

A simulated three-dimensional radiation pattern at 8.3 GHz is shown in Fig. 8. In this simulation, a Hertzian dipole oriented along the x -axis is placed at the origin within the structure depicted in Fig. 1. The excited electric field from the Hertzian dipole couples into the TM_0 mode. Under reciprocal conditions, the radiation pattern would exhibit symmetry in both the $x-z$ and $x-y$ planes. However, the observed pattern clearly lacks symmetry in the $x-z$ plane indicating nonreciprocal behavior. Symmetry is preserved in the $x-y$ plane. This is consistent with expectations because the plasma does not introduce nonreciprocity when the magnetic bias is parallel to the wave vector k_y (Faraday configuration). As expected for a one-dimensional leaky-wave system, the radiation forms a fan-shaped beam confined to the $x-z$ plane with maxima occurring only within this plane. The frequency of 8.3 GHz is of particular interest because it is slightly higher than the upper hybrid frequency ω_{uh} , which marks the resonance frequency of the lower branch of the X-mode. This frequency region also coincides with a strong gain nonreciprocity (truly nonreciprocal) predicted by the dispersion relation.

In Fig. 9, the measured radiation patterns at 4.95 GHz under two distinct conditions represent: magnetized plasma and unmagnetized plasma. In the reciprocal scenario with no magnetic field, S_{21} and S_{12} are equal due to inherent symmetry. A significant gain nonreciprocity of approximately 5 dB is measured for magnetized plasma, where S_{12} significantly exceeds S_{21} . This is consistent with the trend observed in Fig. 5a).

The radiation pattern in unmagnetized plasma closely resembles the S_{12} pattern obtained under magnetic bias.

This similarity arises from the dispersion relation (Fig.

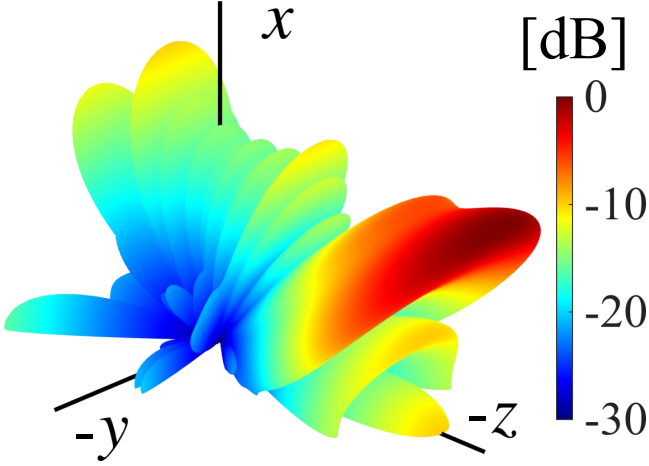


Fig. 9. Simulated normalized 3D radiation pattern generated by a Hertzian dipole oriented along x -axis located at origin at 8.3 GHz.

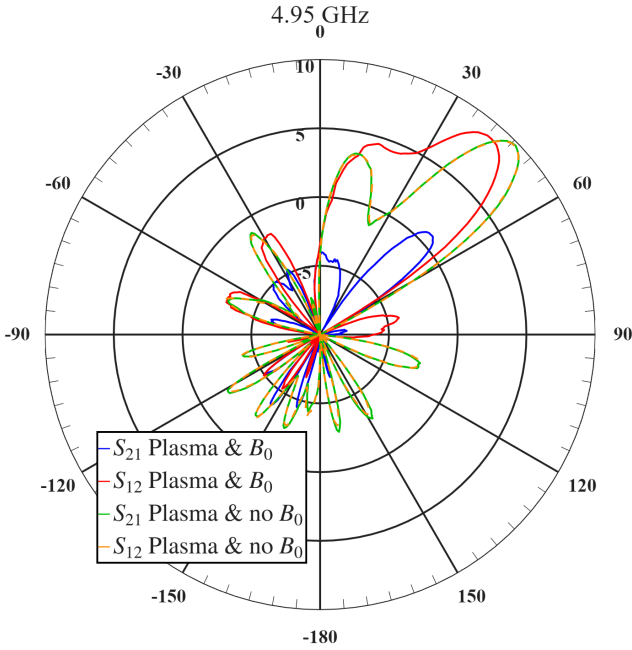


Fig. 10. Radiations pattern with excitation from $\theta = -90^\circ$ in the E-plane measured at 4.95 GHz. Two cases are shown here: S_{21} and S_{12} of magnetized plasma, and S_{21} and S_{12} of unmagnetized plasma. For the unmagnetized plasma case, the curves are coincident.

2), which indicates that radiation below 6 GHz originates from the reflections and scattering at the dielectric-plasma interface. While this radiation mechanism remains symmetric in unmagnetized plasma, the introduction of magnetic bias breaks this symmetry and yields the observed differential gain. The unmagnetized case shows slightly higher gain because magnetization causes more electron collisions by increasing electron density, which increases plasma losses.

B. Fields

Simulated electric field distributions generated by Hertzian dipoles at frequencies of 4.95 GHz and 8.3 GHz are depicted

in Fig. 10. These results can be directly compared with the field distributions obtained from the dispersion relation in Fig. 2, which represent the ideal modal fields of the structure. While the dispersion-based fields describe the eigenmode behavior of the system, the HFSS simulations include the finite excitation and full-wave interactions with the surrounding environment. Nevertheless, the propagation characteristics predicted by the dispersion analysis are clearly reproduced.

At 4.95 GHz, the simulated field remains tightly bound to the interface in both propagation directions. This behavior agrees with the dispersion-derived field distribution at the same frequency, which predicts a slow surface wave close to the vacuum light line. Despite this strong confinement, asymmetric radiation into the semi-infinite air region is observed. The leakage is stronger to the left ($+z$ direction) of the dipole source, which is consistent with the asymmetric dispersion relation predicting different propagation constants for the two directions.

In contrast, the field distribution at 8.3 GHz exhibits predominantly unidirectional radiation toward the right ($-z$ direction) with only weak surface-wave coupling along the interface. This behavior matches the dispersion-based prediction of a truly nonreciprocal leaky mode located between the lower and upper X-mode branches. It is simulated that the directivity exceeds 40 dB at this frequency with a directivity asymmetry of more than 30 dB. This behavior is only observed under ideal conditions: a perfectly uniform plasma frequency, a constant magnetic bias, and a low collision frequency. Experimental radiation patterns weakly capture this effect due to the limitations of practical realization in this frequency band. Nonuniform spatial distributions of both magnetic bias field and plasma density cause shifting of the operating region in the frequency domain. Additionally, significant losses arise from a collision frequency approximately one order of magnitude below the plasma frequency. Together with the imperfect coupling efficiency between the excitation mechanism and the desired surface/leaky modes, this leads to lower measured nonreciprocity.

C. Discussion

Computational and experimental analyses confirm the existence and characteristics of nonreciprocal leaky waves in the magnetized plasma geometry. The results exhibit strong agreement with theoretical predictions. Three distinct radiation mechanisms govern the observed behavior. The first mechanism, observed at frequencies such as 4.95 GHz (Fig. 10a), arises due to reflections of the wave that is fed at the dielectric-plasma interface exhibiting a direction-dependent surface impedance. This enables radiation and manifests as a leaky wave bound to the surface but radiating asymmetrically during propagation [45]. This is a direct consequence of dispersion relation differences for forward and backward directions. The second one is described by the backward wave entering the dielectric and vacuum light cone in the bands from 3.5 – 8.2 GHz and 5 – 8.2 GHz, respectively. The third mechanism involves a true nonreciprocal mode occurring between the lower and upper branches of the X-mode. For

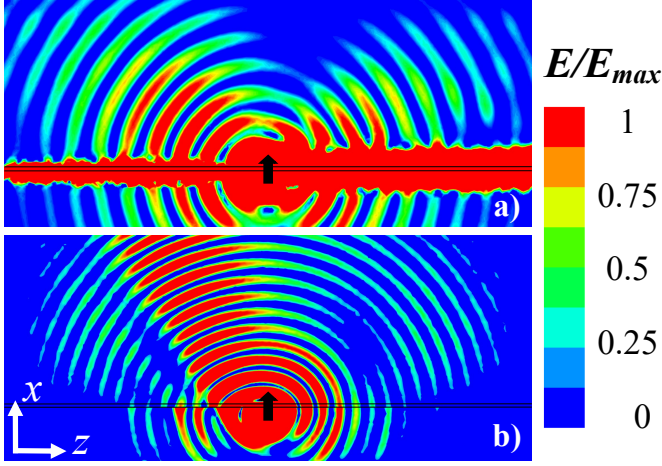


Fig. 11. Electric field plot in the $x - z$ plane with Hertzian dipole excitation at a) 4.95 GHz and b) 8.3 GHz. The dipole is located at the interface of the three materials: vacuum in the upper half-space, dielectric in the middle and magnetized plasma in the lower half-space.

TABLE I
RADIATION MECHANISM

Region	Frequency	Δ Gain (sim)	Radiation Mechanism
I	2 – 4 GHz	0 dB	Scattering
II	4 – 6 GHz	5 dB	Scattering + Backward Wave
III	6 – 8 GHz	–4 dB	Backward Wave
IV	8 – 9 GHz	–5 dB	Truly Nonreciprocal Mode

example, it occurs at 8.3 GHz (Fig. 10b) and is consistent with analytical predictions [28]. Enhanced wave confinement and radiation characteristics in this study are facilitated by using a dielectric layer exhibiting slightly negative permittivity.

The dispersion relation further dictates beam directionality. Across most frequencies, the positive group velocity yields a beam angle increasing relative to the surface normal. However, a distinct backward wave region with negative group velocity exists that causes the beam to transition from endfire towards broadside radiation within a specific band.

Significant performance improvements remain achievable. The proximity of collision frequency to plasma frequency (within one order of magnitude), combined with dielectric and conductor dissipation, severely degrades radiation efficiency. Utilizing lower-loss plasma sources such as solid-state implementations could mitigate this. Furthermore, replacing the cylindrical structure with a planar geometry would eliminate parasitic magnetic field vector components, yielding more consistent radiation patterns and gain measurements and facilitating fabrication.

Additional simulations investigating the influence of the ground plane geometry are provided in the Supplementary Material (Fig. 13). These results show that partially wrapped ground plane configurations can increase the achievable nonreciprocal gain difference compared to flat or absent ground planes. This indicates that the conductor geometry surrounding the plasma column provides an additional design parameter for controlling the coupling between the launcher and the surface or leaky-wave modes.

Further practical considerations arise when scaling plasma-based devices. Gaseous plasmas may exhibit spatial non-uniformities caused by discharge instabilities, electrode geometry, or gas pressure variations. In addition, magnetic bias fields can deviate from ideal uniformity when permanent magnets or finite coils are used. These effects can modify the local plasma frequency and cyclotron frequency, which in turn perturb the dispersion relation and radiation characteristics. Several mitigation strategies exist. First, carefully designed discharge geometries and dielectric confinement structures can improve plasma uniformity over the interaction region. Second, planar magnetic circuits or Helmholtz-type coil configurations can provide more uniform bias fields than simple permanent magnet arrangements. Finally, pulsed plasma operation offers an attractive approach since the effective collision frequency and electron temperature are often lower during the afterglow phase, which can significantly reduce microwave losses while maintaining the required electron density [46].

From a device perspective, the degree of nonreciprocity can be further increased through several mechanisms. Increasing the magnetic bias field directly increases the cyclotron frequency and therefore strengthens the gyrotropic response of the plasma, which widens the nonreciprocal band and increases the difference between forward and backward propagation constants. Improved excitation of the surface wave launcher would also increase the effective interaction length between the guided wave and the magnetized plasma, thereby enhancing the observable radiation asymmetry. Another promising approach is the use of engineered plasma distributions or patterned plasma regions that locally modify the dispersion relation and enable stronger directional coupling. In addition to gaseous plasmas, solid-state plasmas (such as semiconductor or two-dimensional electron gas structures) provide a particularly attractive alternative. These systems offer excellent spatial uniformity, higher carrier densities, and compatibility with integrated microwave platforms, which could significantly strengthen the achievable nonreciprocal response while improving device stability and scalability.

Compared to ferrite-based leaky-wave antennas [9], [13], [14], the plasma approach offers several advantages despite lacking linear beam scanning from negative to positive endfire through broadside. A gain advantage exceeding 6 dB is observed at comparable frequencies. Plasma antennas further enable rapid tunability through the plasma density and magnetic bias. Increasing the plasma density shifts the operational band, while the magnetic bias primarily broadens the nonreciprocal region. In addition, gaseous plasmas can be electrically switched on and off, eliminating the permanent magnetic material required in ferrite implementations. Unlike time-modulated systems that rely on active components [18], the proposed magnetized plasma structure achieves nonreciprocity passively in a time-invariant medium, avoiding the need for switches, phase shifters, or circulators.

Table II compares representative nonreciprocal antenna implementations with the proposed magnetized plasma leaky-wave antenna. Both simulated and experimental results are included. The simulations indicate substantially higher efficiency and isolation under ideal plasma conditions, whereas

TABLE II
COMPARISON OF REPRESENTATIVE NONRECIPROCAL ANTENNA IMPLEMENTATIONS.

Method	Bandwidth	Efficiency	Isolation	Scalability	Tunability	Ref.
Magn. Plasma (sim)	10%	90%	5 dB	ω_p, B_0 , geom.	ω_p, B_0	This work
Magn. Plasma (exp)	10%	10%	4 dB	ω_p, B_0 , geom.	ω_p, B_0	This work
Ferrite CRLH	10%	—	12 dB	B_0 , geom.	B_0	[12]
Ferrite TL	2%	50%	10 dB	B_0 , geom.	B_0	[11]
PST Mod	10%	70%	30 dB	SMD, geom.	—	[17]
Ring MTM	5%	—	12 dB	SMD, geom.	—	[13]

the experiment is primarily limited by plasma losses and imperfect coupling.

Ferrite LWAs provide isolation levels above 10 dB with bandwidths of approximately 2% for transmission-line designs and up to 10% for CRLH structures. These antennas generally achieve higher efficiency due to lower material losses but offer limited tunability since their response is mainly controlled by the magnetic bias. Periodic space-time modulation antennas can achieve very high isolation, but their scalability is limited by the operating range of active components. Similar constraints apply to ring metamaterial implementations, where the SMD elements restrict both scalability and tunability.

Plasma antennas provide additional flexibility since both the plasma frequency ω_p and the magnetic bias B_0 can be tuned during operation and scaled over a wide frequency range.

This inherent passivity and tunability support compelling applications. The structure functions effectively as a nonreciprocal antenna for communications based on distinct beam angles for TX and RX, and Simultaneous Transmit and Receive (STAR) systems. Such implementation becomes particularly practical when employing TX and RX beams with equivalent gain levels but differentiated angular orientations, as depicted in Fig. 5. This enables operation in explicit transmit and receive bands without interference. Its nonreciprocal scattering properties are promising for radar cross-section optimization and electronic warfare implementations. For transmit-only antennas, the nonreciprocity intrinsically protects sensitive circuitry without additional front-end protection components such as isolators. The ability to toggle reciprocity by enabling or disabling the magnetic field adds operational flexibility. Collectively, these attributes present a simple, passive pathway to robust nonreciprocal functionality, potentially reducing dependency on active components in future systems.

V. CONCLUSION

This work establishes a waveguide geometry comprised of magnetized plasma, dielectric, and vacuum regions that sustains nonreciprocal leaky wave radiation across multiple frequency bands. Through coupled analytical, computational, and experimental investigations, we demonstrate that the derived dispersion relation accurately predicts observed nonreciprocal radiation bands. These bands arise from distinct fast-wave mechanisms where phase velocity exceeds the propagation constraints of the structure which necessitates radiation and reflections from the dielectric-plasma interface. Experimentally acquired radiation patterns at selected frequencies confirm pronounced nonreciprocity. These measured S_{21} and S_{12} asymmetries directly allow transmit-receive (TX-RX) isolation

inherently enabled due to the electromagnetic structure. Simulated near-field distributions illustrate the underlying physics. At lower frequencies (e.g., 4.95 GHz), fields remain coupled to the interface while exhibiting directional radiation leakage. In contrast, higher frequencies (e.g., 8.3 GHz) generate unidirectional radiation decoupled from the interface. This is defined as a true nonreciprocal mode. Radiation persists without magnetic bias despite reciprocity dictating symmetric S -parameters. With unmagnetized plasma, radiation patterns resemble one direction of the magnetized case. Simulated far-field patterns further confirm the characteristic fan-beam radiation expected for 1D leaky-wave structures. These findings present a viable pathway toward implementing nonreciprocal leaky-wave antennas for several applications. The passive, time-invariant nature of the effect eliminates the need for active components or temporal modulation. Key operational advantages include electronically tunable radiation bands via control of plasma density, bandwidth adjustment via magnetic bias control, and the ability to toggle reciprocity by activating/deactivating the magnetic field. Such capabilities are particularly advantageous for communication systems that require simultaneous transmit/receive (STAR) operation or distinct beam angles for TX and RX. Further, it exhibits intrinsic isolation of TX/RX and can be applied in electronic warfare platforms where nonreciprocal scattering can reduce detectability.

APPENDIX A RESULTS

A. Axial ratio

In Fig. 11 the measured axial ratio for both S_{21} and S_{12} under magnetized plasma conditions is presented. Within the operational band of 4–6.5 GHz, the co-polar to cross-polar ratio demonstrates moderate polarization selectivity characteristic of leaky-wave antennas. The S_{12} configuration exhibits higher gain throughout this region and achieves a peak axial ratio of 12 dB at 5 GHz. A comparable plateau near 10 dB occurs within the upper band. While these values fall below typical leaky-wave antenna performance benchmarks, the deviation stems primarily from geometric constraints. The cylindrical waveguide structure coupled with the quasi-circular surface wave launcher excites non-ideal TM_0 modes containing residual y -component electric fields alongside the dominant $x-z$ plane orientation. This field asymmetry inherently degrades axial ratio performance.

B. Ground plane geometries

The simulated nonreciprocity, quantified as the realized gain difference between forward and backward excitation, is shown

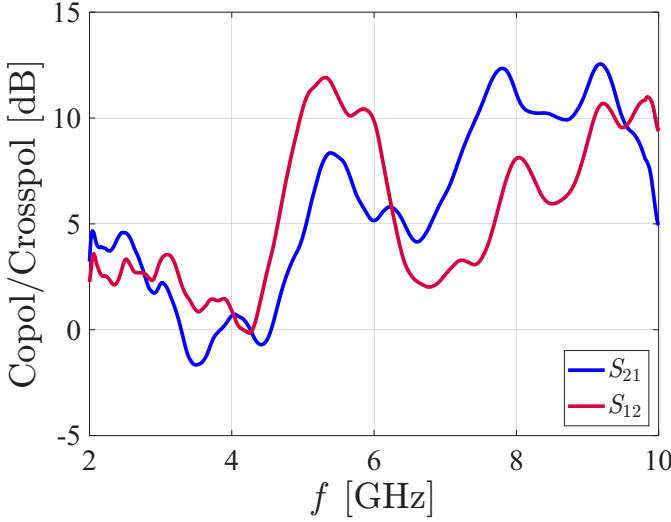


Fig. 12. Measured axial ratio of co-polarization to cross-polarization.

in Fig. 13. The idealized configuration with planar layers provides an upper bound for the achievable nonreciprocity in this structure. However, the simulations also demonstrate that the experimentally investigated bulb configuration can be modified through different ground plane geometries to enhance the directional response. In all cases, the excitation is located at the quartz–vacuum interface at the 12 o’clock position.

Among the investigated geometries, the wrapped ground plane, where the conductor partially surrounds the plasma column, yields the largest gain difference for the truly nonreciprocal mode around 8.5 GHz. This configuration improves coupling between the launcher and the surface wave while simultaneously modifying the local boundary conditions around the plasma column, which enhances the gain asymmetry. In contrast, the flat ground plane beneath the plasma column behaves similarly to the case without a ground plane. In these configurations, the nonreciprocal response is less pronounced, particularly for the truly nonreciprocal mode. These results indicate that the ground plane geometry provides an additional design parameter to tune the degree of nonreciprocity without modifying the plasma parameters.

REFERENCES

- [1] D. R. Jackson, C. Caloz, and T. Itoh, “Leaky-wave antennas,” *Proceedings of the IEEE*, vol. 100, p. 2194–2206, July 2012.
- [2] F. Monticone and A. Alù, “Leaky-wave theory, techniques, and applications: From microwaves to visible frequencies,” *Proceedings of the IEEE*, vol. 103, p. 793–821, May 2015.
- [3] D. M. Pozar, *Microwave engineering*. Hoboken, NJ: Wiley, fourth edition, ed., 2012.
- [4] A. Kord, D. L. Sounas, and A. Alu, “Microwave nonreciprocity,” *Proceedings of the IEEE*, vol. 108, p. 1728–1758, Oct. 2020.
- [5] F. Li, R. J. Davis, S. M. Kandil, and D. F. Sievenpiper, “Electromagnetic nonreciprocity in a magnetized plasma circulator,” *Physical Review Applied*, vol. 18, p. 064066, Dec. 2022.
- [6] R. Karimian, S. Taravati, M. D. Ardakani, S. Ahmadi, and M. E. Zaghlool, “Nonreciprocal-beam phased-array antennas based on transistor-loaded phase shifters,” *IEEE Transactions on Antennas and Propagation*, vol. 69, p. 7572–7581, Nov. 2021.
- [7] Y.-L. Chang and Q.-X. Chu, “Ferrite-loaded dual-polarized antenna for decoupling of multiband multiarray antennas,” *IEEE Transactions on Antennas and Propagation*, vol. 69, p. 7419–7426, Nov. 2021.

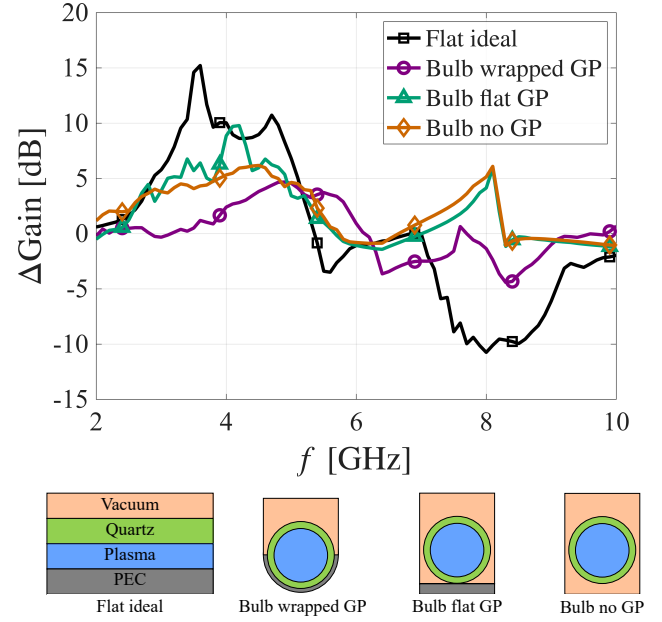


Fig. 13. Simulated realized gain difference for different ground plane geometries and for the idealized planar configuration. The inset illustrates the cross sections of the investigated ground plane configurations.

- [8] T. Kodera and C. Caloz, “Dual-band full-space scanning leaky-wave antenna based on ferrite-loaded open waveguide,” *IEEE Antennas and Wireless Propagation Letters*, vol. 8, p. 1202–1205, 2009.
- [9] T. Kodera and C. Caloz, “Uniform ferrite-loaded open waveguide structure with crlh response and its application to a novel backfire-to-endfire leaky-wave antenna,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, p. 784–795, Apr. 2009.
- [10] L. Hong, Y. You, Q. Shen, Y. Wang, X. Liu, H. Zhang, C. Wu, L. Shen, X. Deng, and S. Xiao, “Magnetic field assisted beam-scanning leaky-wave antenna utilizing one-way waveguide,” *Scientific Reports*, vol. 9, p. 16777, Nov. 2019.
- [11] N. Apaydin, K. Sertel, and J. L. Volakis, “Nonreciprocal leaky-wave antenna based on coupled microstrip lines on a non-uniformly biased ferrite substrate,” *IEEE Transactions on Antennas and Propagation*, vol. 61, p. 3458–3465, July 2013.
- [12] N. Apaydin, L. Z. Lee, K. Sertel, and J. L. Volakis, “Nonreciprocal and magnetically scanned leaky-wave antenna using coupled crlh lines,” in *2013 IEEE Antennas and Propagation Society International Symposium (APSURSI)*, p. 2297–2298, July 2013. ISSN: 1947-1491.
- [13] T. Kodera, D. L. Sounas, and C. Caloz, “Nonreciprocal magnetless crlh leaky-wave antenna based on a ring metamaterial structure,” *IEEE Antennas and Wireless Propagation Letters*, vol. 10, p. 1551–1554, 2011.
- [14] Y. Yokohama and T. Kodera, “Voltage beam-steerable leaky-wave antenna using magnet-less non-reciprocal metamaterial (mnm),” in *2015 International Symposium on Antennas and Propagation (ISAP)*, p. 1–3, Nov. 2015.
- [15] Z. Xu, M. Wang, S. Fang, H. Liu, Z. Wang, and D. F. Sievenpiper, “Broadside radiation from chern photonic topological insulators,” *IEEE Transactions on Antennas and Propagation*, vol. 70, p. 2358–2363, Mar. 2022.
- [16] J. Han, F. Liang, D. Huang, Y. Zhao, J. Liu, D. Zhao, and B.-Z. Wang, “Topological traveling-wave radiation based on chiral edge states in photonic chern insulators,” *Optics Letters*, vol. 49, p. 6233–6236, Nov. 2024.
- [17] S. Taravati and C. Caloz, “Mixer-duplexer-antenna leaky-wave system based on periodic space-time modulation,” *IEEE Transactions on Antennas and Propagation*, vol. 65, p. 442–452, Feb. 2017.
- [18] M. Q. Dinh and M. Thuy Le, “Surface plasmon polaritons in time-modulated metallic materials for non-reciprocal controllable leaky-wave antennas,” *IEEE Access*, vol. 10, p. 28461–28470, 2022.
- [19] A. J. Park, C. C. Pfeiffer, A. A. Chabanov, and A. Grbic, “Simultaneous transmit-receive horn antenna based on a nonreciprocal metasurface with

- embedded magnetic bias,” in *2024 IEEE International Workshop on Antenna Technology (iWAT)*, p. 43–46, Apr. 2024.
- [20] S. A. Maier, *Plasmonics: Fundamentals and Applications*. New York: Springer US, 1. Aufl. ed., 2007.
- [21] A. R. Davoyan and N. Engheta, “Theory of wave propagation in magnetized near-zero-epsilon metamaterials: Evidence for one-way photonic states and magnetically switched transparency and opacity,” *Physical Review Letters*, vol. 111, p. 257401, Dec. 2013.
- [22] S. Pakniyat, A. M. Holmes, G. W. Hanson, S. A. H. Gangaraj, M. Antezza, M. G. Silveirinha, S. Jam, and F. Monticone, “Non-reciprocal, robust surface plasmon polaritons on gyrotropic interfaces,” *IEEE Transactions on Antennas and Propagation*, vol. 68, p. 3718–3729, May 2020.
- [23] K. Shastri, M. I. Abdelrahman, and F. Monticone, “Nonreciprocal and topological plasmonics,” *Photonics*, vol. 8, p. 133, Apr. 2021.
- [24] J. J. Brion, R. F. Wallis, A. Hartstein, and E. Burstein, “Theory of surface magnetoplasmons in semiconductors,” *Physical Review Letters*, vol. 28, p. 1455–1458, May 1972.
- [25] M. A. Cappelli, H. M. Bernety, D. Sun, L. Houriez, and B. Wang, “Tunable non-reciprocal waveguide using spoof plasmon polariton coupling to a gaseous magnetoplasmon,” *Optics Letters*, vol. 48, p. 3725–3728, July 2023.
- [26] H. Mehrpour Bernety, D. Murphy Zink, D. Piriaei, and M. A. Cappelli, “Experimental detection of topological surface waves at a magnetized plasma interface in the voigt configuration,” *Applied Physics Letters*, vol. 124, p. 043102, Jan. 2024.
- [27] N. Han, J. Liu, Y. Gao, K. Zhou, and S. Liu, “Topological transitions in magnetized plasma and optical isolators based on leaky waveguide plasmon mode,” *Physical Review B*, vol. 106, p. 165306, Oct. 2022.
- [28] S. Ali Hassani Gangaraj and F. Monticone, “Topologically-protected one-way leaky waves in nonreciprocal plasmonic structures,” *Journal of Physics: Condensed Matter*, vol. 30, p. 104002, Mar. 2018.
- [29] Y. Raizer, J. Allen, and V. Kisin, *Gas Discharge Physics*. Springer Berlin Heidelberg, 2011.
- [30] H. Conrads and M. Schmidt, “Plasma generation and plasma sources,” *Plasma Sources Science and Technology*, vol. 9, p. 441, Nov. 2000.
- [31] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*. Wiley, 1 ed., Apr. 2005.
- [32] V. S. Asadchy, M. S. Mirmoosa, A. Díaz-Rubio, S. Fan, and S. A. Tretyakov, “Tutorial on electromagnetic nonreciprocity and its origins,” *Proceedings of the IEEE*, vol. 108, no. 10, pp. 1684–1727, 2020.
- [33] J. A. Bittencourt, *Fundamentals of Plasma Physics*. Fundamentals of Plasma Physics, Third Edition by J.A. Bittencourt. Published by Springer-Verlag, New York, Inc.; 2004. ISBN 0-387-20975-1., third ed., 2004.
- [34] A. Fox, *Optical Properties of Solids*. Oxford master series in condensed matter physics, Oxford University Press, 2001.
- [35] M. G. Silveirinha, S. A. H. Gangaraj, G. W. Hanson, and M. Antezza, “Fluctuation-induced forces on an atom near a photonic topological material,” *Physical Review A*, vol. 97, p. 022509, Feb. 2018.
- [36] A. A. Oliner and T. Tamir, “Backward waves on isotropic plasma slabs,” *Journal of Applied Physics*, vol. 33, p. 231–233, Jan. 1962.
- [37] A. W. Trivelpiece and R. W. Gould, “Space charge waves in cylindrical plasma columns,” *Journal of Applied Physics*, vol. 30, p. 1784–1793, Nov. 1959.
- [38] S. M. Mikki and A. A. Kishk, “Electromagnetic wave propagation in nonlocal media: Negative group velocity and beyond,” *Progress In Electromagnetics Research B*, vol. 14, p. 149–174, 2009.
- [39] S. G. Rautian, “Reflection and refraction at the boundary of a medium with negative group velocity,” *Physics-Uspekhi*, vol. 51, p. 981–988, Oct. 2008.
- [40] L. Brillouin, *Wave Propagation and Group Velocity*. Pure and applied physics, Academic Press, 1960.
- [41] C. Angulo and W. Chang, “The launching of surface waves by a parallel plate waveguide,” *IRE Transactions on Antennas and Propagation*, vol. 7, p. 359–368, Oct. 1959.
- [42] J. A. Rodriguez, *Electromagnetic Wave Manipulation with Plasma Metamaterials*. Ph.D., Stanford University, United States – California, 2023.
- [43] M. Howlader, Y. Yang, and J. Roth, “Time-resolved measurements of electron number density and collision frequency for a fluorescent lamp plasma using microwave diagnostics,” *IEEE Transactions on Plasma Science*, vol. 33, p. 1093–1099, June 2005.
- [44] K. N. Leung, T. K. Samec, and A. Lamm, “Optimization of permanent magnet plasma confinement,” *Physics Letters A*, vol. 51, p. 490–492, May 1975.
- [45] H. Mehrpour Bernety and M. A. Cappelli, “An electromagnetic scattering approach to identifying topological and non-topological unidirectional edge states at gyrotropic plasma interfaces,” *Journal of Applied Physics*, vol. 133, p. 104902, 03 2023.
- [46] V. Podolsky, A. Khomenko, and S. Macheret, “Time-resolved measurements of electron number density in argon and nitrogen plasmas sustained by high-voltage, high repetition rate, nanosecond pulses,” *Plasma Sources Science and Technology*, vol. 27, p. 10LT02, Oct. 2018.



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