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Nonreciprocal Radiation from an Axial-Mode Helical Antenna Embedded in Magnetized Plasma

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Abstract—An axial-mode helical antenna embedded in a low-pressure magnetized plasma is experimentally shown to produce nonreciprocal circularly polarized radiation in the C band. The plasma column is placed along the helix axis and biased by a static magnetic field of approximately 100 mT, so that the radiated wave interacts with the plasma in the Faraday configuration. Control measurements with no plasma and with unmagnetized plasma show reciprocal transmit (TX) and receive (RX) responses. When the plasma is magnetized, the broadside LHCP response becomes strongly direction dependent. The measured TX/RX contrast reaches approximately 20 dB near 5 GHz, with a practical operating point near 5.1 GHz showing about 15 dB isolation and about 3 dB insertion loss relative to the no-plasma antenna. Full-wave simulations using a collisional gyrotropic plasma model reproduce the measured trends and show that the nonreciprocity is concentrated along the magnetically biased main-beam direction. These results demonstrate a compact plasma-loaded circularly polarized antenna in which the radiating element and nonreciprocal medium are integrated into the same structure.

Index Terms—Microwave plasma interaction, magnetized plasma, gyrotropic media, nonreciprocal media, circular polarization, plasma antennas, helix antenna.

I. INTRODUCTION

NONRECIPROCAL antennas provide different transmitting and receiving responses when the direction of power flow is reversed. This behavior is not available from a passive, linear, time-invariant antenna made only from reciprocal materials, but it is useful when the antenna itself must contribute to isolation, interference rejection, or polarization selectivity at the front end of a radio system. Prior antenna-level demonstrations have used angular-momentum-biased inclusions, ferrite loading, and spatiotemporal modulation to break reciprocity [1], [2], [3], [4]. These approaches have shown that nonreciprocity can be introduced directly into a radiating aperture, rather than only in a separate isolator or circulator.

Magnetized plasma is another route to nonreciprocal electromagnetic response. A static magnetic bias makes the plasma gyrotropic, so waves propagating along the bias field decompose into two circularly polarized eigenwaves with different propagation constants and loss. This is the same basic mechanism that produces Faraday rotation in magnetized media [5]. Compared with conventional solid-state gyrotropic media, gaseous plasma offers electrical tunability through the electron

density, and can be switched on and off. Recent work has used magnetized plasma to realize nonreciprocal surface waves and waveguide isolation [6], [7]. However, using this gyrotropic response directly inside a circularly polarized radiating antenna remains largely unexplored.

Plasma antennas have been studied extensively, but most prior work uses the plasma as a reconfigurable conductor, reflector, or loading element [8], [9], [10], [11]. Helical plasma antennas and plasma-loaded helices have also been investigated for beam steering, frequency tuning, and radiation control [12], [13], [14]. More recently, magnetized plasma has been used to demonstrate nonreciprocal leaky-wave radiation, where the magnetic bias modifies the propagation and leakage of a guided surface wave before radiation occurs [15]. In contrast, the present work places the gyrotropic medium inside the radiating aperture itself.

This letter demonstrates such a structure. An axial-mode helix is wrapped around a low-pressure discharge tube and magnetized along its axis, so that the antenna and the nonreciprocal medium are colocated: the helix radiates circular polarization along the same direction in which the plasma is gyrotropic. Measurements compare no-plasma, unmagnetized-plasma, and magnetized-plasma cases under identical geometry. The first two remain nearly reciprocal, while the magnetized case produces strong broadside TX/RX contrast in LHCP gain together with a reversal of the received polarization state, consistent with circular-eigenwave splitting. The measured gain, isolation, insertion loss, and cross-polarization discrimination are supported by full-wave simulations using a collisional cold-plasma tensor model. The result is not a separate isolator attached to an antenna, but an antenna whose radiation and reception are directly modified by the biased plasma column.

II. MAGNETIZED PLASMA MODEL

For a cold, magnetized plasma biased by a static magnetic field $\mathbf{B}_0 = B_0 \hat{\mathbf{z}}$, the relative permittivity tensor is written as [5], [16]:

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

Including an effective electron collision frequency ν , with the electron plasma and cyclotron frequencies defined as $\omega_p = \sqrt{n_e e^2 / (m_e \varepsilon_0)}$ and $\omega_c = eB_0 / m_e$, respectively, the tensor

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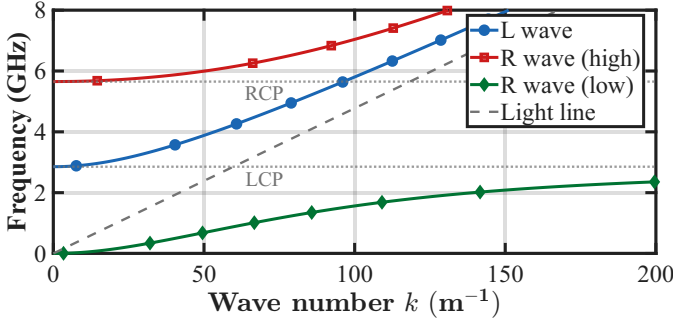


Fig. 1. Calculated dispersion relation of the circularly polarized eigenwaves for the plasma parameters used in the model.

elements are

$$\varepsilon_t = 1 - \frac{\omega_p^2(\omega + i\nu)}{\omega[(\omega + i\nu)^2 - \omega_c^2]}, \quad (2)$$

$$\varepsilon_g = \frac{\omega_p^2\omega_c}{\omega[(\omega + i\nu)^2 - \omega_c^2]}, \quad (3)$$

$$\varepsilon_a = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu)}. \quad (4)$$

The off-diagonal term ε_g lifts the degeneracy between the two circularly polarized eigenwaves.

For propagation parallel to $\mathbf{B}_0$, the transverse eigenwaves are circularly polarized and have propagation constants

$$k_{\pm} = k_0\sqrt{\varepsilon_t \pm \varepsilon_g}. \quad (5)$$

Thus, the two handednesses experience different phase constants, cutoffs, and attenuation, as illustrated in Fig. 1: in the band used here, one circular eigenwave is strongly attenuated while the other remains supported. The key point for the antenna experiment is that the handedness of a circularly polarized wave is defined with respect to its propagation direction, while the magnetic bias is fixed in the laboratory frame. A wave leaving the helix and a wave incident on it therefore couple to different plasma eigenmodes. In a reciprocal dielectric or an unmagnetized lossy plasma, reversing the propagation direction preserves the power transfer after accounting for ordinary loss; in the magnetized case, the gyrotropic term produces different attenuation and polarization conversion for TX and RX. This is the mechanism for the measured transmit/receive asymmetry. Accordingly, reversing the magnetic bias interchanges the source and observation responses, consistent with the Onsager–Casimir relation $S_{ij}(\mathbf{B}_0) = S_{ji}(-\mathbf{B}_0)$ [17]; the simulated RX results below are obtained in exactly this way.

III. EXPERIMENTAL REALIZATION

The experimental structure is shown in Fig. 2. The available plasma tube has an outer diameter of approximately 16 mm and therefore sets the minimum diameter of the surrounding helix. An 18 mm helix diameter gives a circumference close to one free-space wavelength near 5 GHz, placing the antenna in the axial-mode regime within the desired measurement band. The left-hand circularly polarized helix has 7.5 turns and a 17 mm pitch and is fed by a coaxial line through a circular

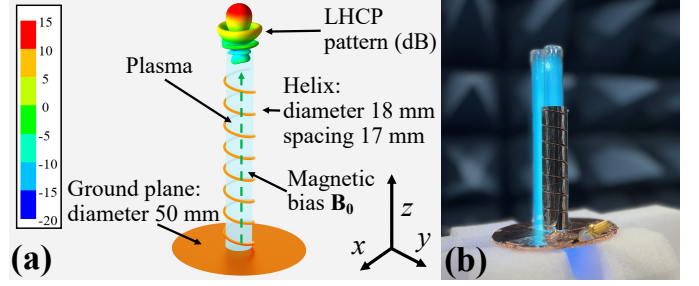


Fig. 2. (a) Schematic of the plasma-loaded axial-mode helix with magnetic bias along the helix axis. (b) Photograph of the experimental antenna and discharge tube.

ground plane with a diameter of 50 mm. A 3-D printed PLA support fixes the pitch and keeps the helix concentric with the plasma tube.

The plasma is produced by a U-shaped ultraviolet discharge tube with an active length of approximately 200 mm. The electrodes are located near one end of the lamp, leaving the principal radiating region free of electrode loading. The tube is driven continuously by electronic ballasts during the microwave measurements, so the RF field interacts with a quasi-steady low-pressure discharge. The discharge consists of mercury-doped argon at a pressure of approximately 250 Pa [18], and the surrounding quartz wall is approximately 1 mm thick with a relative permittivity of 3.8. Although all measurements in this work were performed under steady-state continuous-wave (CW) conditions, the plasma can in principle be switched. Its response time is physically limited by the ionization and recombination time constants of low-pressure Hg–Ar discharges, which are on the order of tens of microseconds [19].

Prior to the antenna measurements, the same discharge tube was independently characterized in a WR-187 waveguide fixture. Its measured complex S_{11} , S_{21} , and S_{22} responses were fitted using an HFSS model of a homogeneous collisional plasma, yielding the effective parameters $n_e = 2 \times 10^{17} \text{ m}^{-3}$ and $\nu = 2 \text{ GHz}$. These values agree with microwave diagnostics reported for comparable fluorescent-lamp discharges [16], [20], [21] and were fixed before the antenna simulations. This tube was selected because these parameters, together with the available 100 mT bias, place the nonreciprocal window over the helix operating band, and because its comparatively low collision rate limits collisional absorption. The two cutoffs marked in Fig. 1 bound this window. For the parameters used here it extends from 2.85 GHz (LCP cutoff) to 5.65 GHz (RCP cutoff), so the measured band lies inside it, below the upper edge. Both cutoffs scale with n_e and B_0 : reducing n_e by 25% lowers the RCP cutoff to 5.15 GHz, which would move the upper part of the measured band out of the window and remove the eigenwave contrast there, whereas increasing n_e by 25% raises it to 6.10 GHz; a $\pm 10\%$ change in B_0 shifts it by about $\pm 0.19 \text{ GHz}$. The existence of the TX/RX asymmetry nevertheless follows from the gyrotropy itself and not from the precise values.

A Helmholtz coil supplies the static field along the helix axis. The coils have an inner diameter of approximately

20 cm and a separation of approximately 15 cm. During the magnetized-plasma measurements, the measured central field was approximately 100 mT, with an axial variation of at most ± 10 mT over the active helix length. This aligns the main beam of the axial-mode helix approximately parallel to $\mathbf{B}_0$, placing the antenna in the Faraday geometry. The windings are approximately 10 cm from the helix axis, and the coil assembly remained physically in place, de-energized, for the no-plasma and unmagnetized-plasma measurements, so any scattering from the coil is common to all three states and cancels in the TX/RX comparison. The axial field profile was supplied by the coil manufacturer and verified with a Hall probe.

Broadside measurements are performed with a vector network analyzer using a 10 kHz IF bandwidth and an averaging factor of 16. A dual-polarized horn is positioned approximately 2 m from the helix in the far field. The two complex linear responses of the horn are denoted by E_x and E_y , from which the circularly polarized components are reconstructed as

$$E_{\text{LHCP}} = \frac{E_x + jE_y}{\sqrt{2}}, \quad E_{\text{RHCP}} = \frac{E_x - jE_y}{\sqrt{2}}. \quad (6)$$

The polarization convention is referenced to the direction of propagation and is applied consistently to both measurement directions. TX denotes propagation from the helix to the horn, whereas RX denotes propagation from the horn to the helix. The experimental geometry is reproduced in HFSS using the plasma tensor in (1)–(4).

IV. RESULTS AND DISCUSSION

The measured broadside LHCP gain is shown in Fig. 3(a). The no-plasma case provides the reference response of the axial-mode helix, while the unmagnetized-plasma case isolates the effect of ordinary plasma loading and collisional loss. Both control cases are nearly reciprocal: the TX and RX curves follow the same trend over the measured band. This confirms that the measurement geometry and the unmagnetized discharge do not by themselves produce a large direction-dependent response.

When the plasma is magnetized, the response changes qualitatively. The TX gain remains comparable to the unmagnetized-plasma case over much of the band, while the RX gain is strongly suppressed. This behavior is the key effect of the gyrotropic plasma loading: the magnetic bias changes the circular eigenwaves seen by the outgoing and incoming fields, causing the helix to radiate and receive differently in the same broadside direction.

All measured curves are the mean of 12 independent runs, each plasma run using a separate ignition and warm-up; the shaded bands give the corresponding ± 1 standard deviation. Isolation and XPD are formed run by run before averaging, so their spread reflects the paired TX/RX variation rather than the sum of two independently averaged curves. The no-plasma case is stable to within a few tenths of a decibel, whereas the plasma cases fluctuate more, consistent with temporal plasma variation, thermal drift of the discharge, and the known flicker noise of low-pressure lamps [16]. The reported isolation lies well outside this spread.

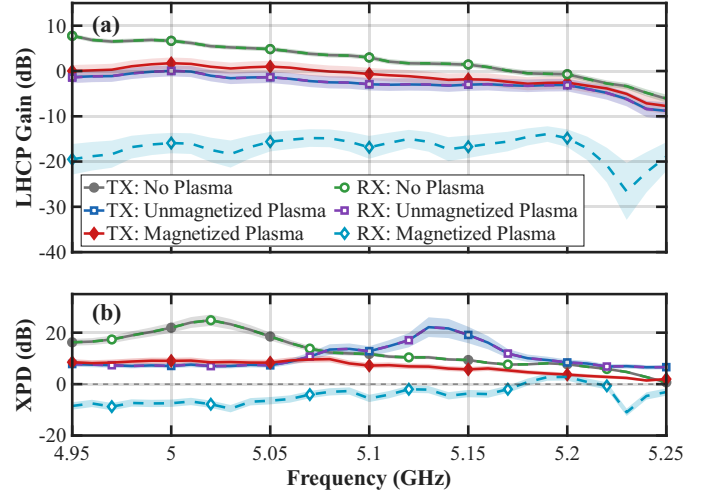


Fig. 3. (a) Measured broadside LHCP gain for no plasma, unmagnetized plasma, and magnetized plasma. TX denotes propagation from the helix to the horn; RX denotes propagation from the horn to the helix. (b) Measured cross-polarization discrimination for no plasma, unmagnetized plasma, and magnetized plasma. Negative XPD indicates that the RHCP component is larger than the LHCP component. Solid curves are the mean over 12 independent runs; shaded bands are ± 1 standard deviation.

The measured cross-polarization discrimination

$$\text{XPD} = G_{\text{LHCP}} - G_{\text{RHCP}} \quad (7)$$

is shown in Fig. 3(b). The no-plasma helix has high LHCP purity near the lower part of the band, as expected for an axial-mode helix. The unmagnetized plasma shifts the polarization response but remains reciprocal. With magnetized plasma, the TX and RX polarization responses are no longer the same: in RX the XPD becomes negative over much of the band, so the received field at the helix is dominated by the opposite circular component. Because the LHCP and RHCP components are reconstructed from the two complex orthogonal horn channels, this is a polarization-resolved measurement of the nonreciprocal response rather than a power-only comparison. The behavior is consistent with the circular-eigenwave splitting in Fig. 1, where the magnetized plasma attenuates and phase-shifts the two circular components differently depending on the direction of propagation, and with direction-dependent coupling between the helix and the gyrotropic plasma. Together with the reciprocal no-plasma and unmagnetized-plasma controls, this supports the proposed circular-eigenwave mechanism.

The broadside TX/RX isolation and the insertion loss relative to the no-plasma transmit case are defined from the measured LHCP gain as

$$I_{\text{TX/RX}} = G_{\text{TX,LHCP}}^{B_0} - G_{\text{RX,LHCP}}^{B_0}, \quad (8)$$

$$L_{\text{ins}} = G_{\text{TX,LHCP}}^{\text{no plasma}} - G_{\text{TX,LHCP}}^{B_0}, \quad (9)$$

where all quantities are in dB; larger $I_{\text{TX/RX}}$ and smaller L_{ins} are preferred.

The extracted isolation and insertion loss are shown in Fig. 4. The isolation reaches approximately 20 dB near the lower end of the measured band and remains on the order of 10–20 dB across most of the band, while the insertion loss decreases with frequency; a useful tradeoff occurs near

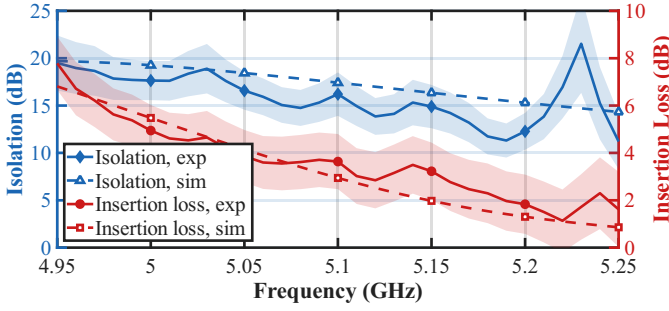


Fig. 4. Measured and simulated broadside TX/RX isolation and insertion loss for the magnetized-plasma case.

5.1 GHz, where the measured response gives approximately 15 dB isolation with about 3 dB insertion loss. The simulated curves follow the measured trend. The decreasing insertion loss is driven primarily by the plasma-induced upward shift of the helix polarization optimum, visible in the XPD peak moving from approximately 5.0 to 5.13–5.15 GHz, and by main-beam redistribution, since the no-plasma broadside gain decreases more rapidly toward the upper end of the band than the magnetized-TX gain. Reduced attenuation of the TX-supported eigenwave and frequency-dependent coupling to the finite plasma column contribute a smaller share of the trend.

Fig. 5(a) shows the simulated LHCP radiation pattern at 5.1 GHz. The no-plasma antenna has the expected axial-mode main beam. The unmagnetized plasma reduces the gain but does not create a large TX/RX difference. With magnetized plasma, the TX and RX patterns separate strongly near boresight. The TX pattern remains directed along the helix axis, while the RX pattern is strongly reduced and distorted in the main-beam region. The difference becomes smaller at large off-axis angles, where the wave vector is no longer closely aligned with $\mathbf{B}_0$ and the interaction is no longer purely in the Faraday geometry. Fig. 5(b) quantifies this: the isolation exceeds 10 dB within approximately $\pm 40^\circ$ of boresight, covering the main-beam solid angle. The simulated radiation efficiency at 5.1 GHz is 95% with no plasma, 88% with unmagnetized plasma, and 85% for the magnetized TX case; the magnetized RX value of 65% is obtained by reversing $\mathbf{B}_0$, as described above. Collisional absorption therefore accounts for only about 1 dB of the TX/RX difference and about 0.5 dB of the insertion loss. The remaining contrast arises from polarization conversion and main-beam distortion, visible in Figs. 3(b) and 5: the incident field is not primarily absorbed but converted into the circular component that the LHCP helix rejects.

The measured S_{11} is shown in Fig. 6. Igniting the discharge produces a small but systematic change in both magnitude and phase, consistent with plasma loading of the antenna near field, while applying $\mathbf{B}_0$ changes the response considerably less. The input impedance obtained from the measured complex reflection coefficient, $Z_{\text{in}} = Z_0(1 + S_{11})/(1 - S_{11})$, remains capacitive across the band and shifts by only a few ohms between the three states; the reference plane includes a short coaxial pigtail, which adds a common phase offset to all curves. Since $|S_{11}|$ stays below approximately -6 dB in every

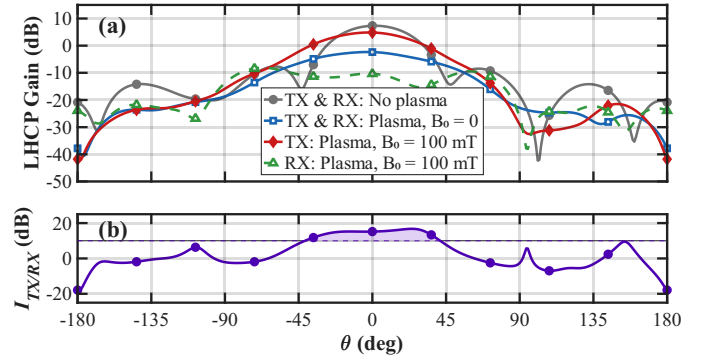


Fig. 5. Simulated LHCP radiation patterns at 5.1 GHz. The magnetized plasma produces a strong TX/RX difference near boresight. (a) radiation pattern, (b) angular variation of TX/RX isolation.

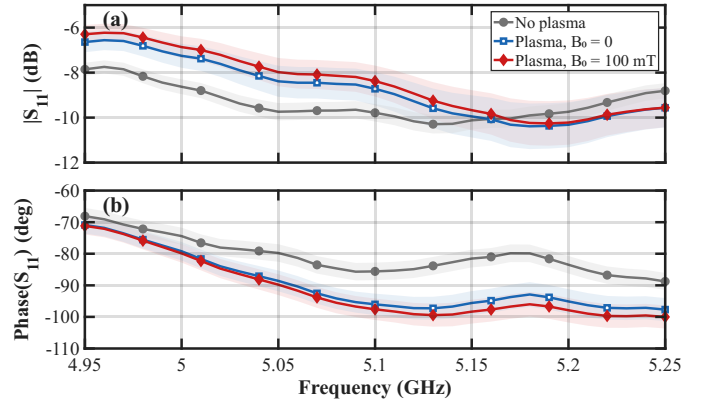


Fig. 6. Measured reflection coefficient for no plasma, unmagnetized plasma, and magnetized plasma. (a) magnitude in dB, (b) phase in degrees.

case, the large TX/RX difference in the magnetized case cannot be attributed to detuning or to a change in input match. Neither S_{11} nor Z_{in} shows a feature near 5.225 GHz, so the narrow isolation maximum at that frequency in Fig. 4, which is reproducible across all runs, does not originate in the antenna input impedance.

V. CONCLUSION

A plasma-loaded axial-mode helix was shown experimentally to radiate and receive nonreciprocally when the plasma is magnetized along the helix axis. The no-plasma and unmagnetized-plasma controls remained reciprocal, and full-wave simulations using a collisional gyrotropic tensor reproduced the measured trends, confirming that the asymmetry originates in the biased plasma and is concentrated along the main-beam direction. The result demonstrates antenna-level nonreciprocity from a medium integrated directly into the radiating structure, which may be useful for reconfigurable front ends, radar receiver protection, and full-duplex links. The present implementation relies on an external Helmholtz coil and a commercial discharge tube and is therefore a proof-of-concept platform; future work should focus on reducing the bias-field hardware, optimizing the plasma geometry, characterizing power handling and linearity at the antenna level, and improving the tradeoff between insertion loss, isolation, and bandwidth.

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