S-Polarized Surface waves in Ferrite bounded by Nonlinear Nonmagnetic Negative Permittivity Metamaterial

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Abstract: In this paper, we studied the S-polarized (TE) nonlinear Magnetostatic surface wave in ferrite bounded by nonlinear nonmagnetic negative permittivity metamaterial. A ferrite layer (YIG) is sandwiched between two thick nonlinear nonmagnetic negative permittivity material layers (NPM). The dispersion relation for TE nonlinear Magnetostatic surface waves (NMSSW) has been derived for the proposed structure and numerically investigated. We found that effective refractive index decreases with thickness and frequency increase. Also, the effective refractive index increases with optical nonlinearity increase and flips to negative values at a certain value of optical nonlinearity. Thus, the structure behaves like a left-handed-material. We found that the power flow is changing by changing the operating frequency, the ferrite thickness, and the optical nonlinearity.

Keywords:*Magnetostatic surface waves MSW; dispersion relation; negative permittivity material NPM; power flow.*

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1. Introduction

New artificial materials that have been investigated recently exhibited both negative permeability and permittivity over a certain range of frequencies. In those materials, there were the wave vector, the electric field, and the magnetic field form a left-handed system. Thus, they were called left-handed materials (LHM).

Recently, a group of researchers at the University of San Diego were able to synthesize an artificial dielectric medium (metamaterials). They were able to demonstrate that those materials exhibit both negative dielectric permittivity and magnetic permeability simultaneously over a certain range of frequencies [1]. By that realization, the prediction of Veselago [2] in his pioneer paper that electromagnetic propagation in an isotropic medium with negative dielectric permittivity $\varepsilon(\omega)<0$ and negative permeability $\mu(\omega)<0$ that could exhibit unusual properties were realized. In such materials (LHM) there appeared the electric field vector E, the magnetic field vector H, and the wave vector k form a left-hand orthogonal set. Those recent demonstrations on the existence of the LHM resulted in the left door being left wide open to unique possibilities in the design of a novel type of device based on electromagnetic wave propagation in those materials, but in a non-conventional way.

Recently, many researchers [3-6] proposed a nonlinear LHM structure, and others [7] have proposed nonmagnetic linear metamaterials. Ferrites represent class of solid ceramic materials that contain crystal structure. Those materials were ferromagnetic; they were considered to be good insulators with high permeability, dielectric constants ranging between 10 and 15 or perhaps larger. In addition, they possessed properties that allowed strong interaction between the magnetic dipole moment associated with the electron spin and the microwave electromagnetic fields. As a result of those interactions, ferrite exhibits nonreciprocal properties such as different phase constant and phase velocities for right and left circularly polarized waves, transmission coefficients that were a function of the direction of propagation, and permeability represented by a tensor rather than a single scalar. Those characteristics turned important in the design of nonreciprocal microwave devices [8, 9].

A growing interest in studying the electromagnetic surface waves of either linear or nonlinear waves of waveguide structure, containing left-handed materials, was motivated by potential applications of those artificial materials [10-19]. Hamada et al (2003) [20] have recently investigated the propagation characteristics of TM nonlinear surface waves in a left-handed material structure. Magnetostatic surface waves [5, 21-24] were also interesting due to their applications in microwave engineering devices such as isolators, circulators, and signal processors.

Recent studies [25] proposed a new class of materials which is nonlinear nonmagnetic negative permittivity materials (NPM). This class of material was inspired by Shadrivov's work and others.

Metamaterials are used in fabricating Transmission lines [26, 27], Microstrip Resonators [28], Couplers [29], Resonators [30], and Antennas [31]. Ferrite with Metamaterials also used to fabricate antenna and other applications [32-34]. These applications motive us to investigate the propagation of TE waves in three layers structure composed of Metamaterial and Ferrite. Thus, we are interested in overall effect of combining both metamaterial and ferrite on three layers structure. Therefore, we study the propagation of TE waves NMSSW in three layered structure were investigated: They were ferrite slab sandwiched between two layers of nonlinear nonmagnetic negative permittivity material (NPM), which might have a potential applications in fabricating antenna, microstrips, and couplers.

This paper is organized as follows: Section 2 we derive the dispersion relation of the surface waves in nonlinear nonmagnetic NPM- a ferrite -nonlinear nonmagnetic NPM structure and the power flow; Section 3 discusses the numerical results; Section 4 is solely devoted to the conclusion.

2. Theory

2.1: The Dispersion Relation

Figure 1, illustrates the geometry and coordinates of the structure under investigation. The cover and the substrate layers, $(z < 0 \text{ and } z > t)$, of the structure are the nonlinear nonmagnetic NPM. We consider nonlinearity varies only in the direction of propagation. The ferrite layer is sandwiched between those layers $(0 < z < t)$. Considered TE polarized wave propagating along the x direction with angular frequency ω and effective nonlinear wave number β.

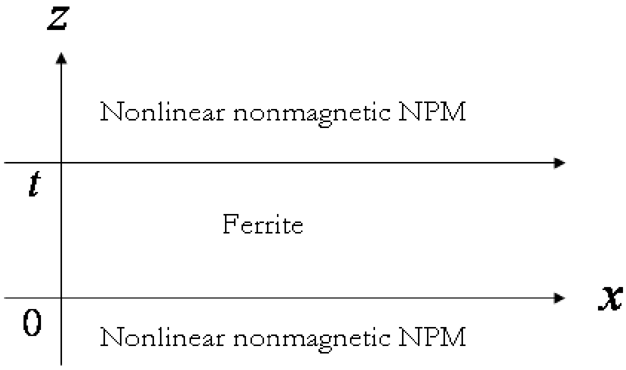

***Figure 1:** The waveguide structure*

The NPM metamaterial has effective Kerr like dielectric constant permittivity, ε_{eff}^{NL} , which is given by [32]

$$\varepsilon_{eff}^{NL} = \varepsilon_D\left(\left|E\right|^2\right) - \frac{\omega_p^2}{\omega^2} \tag{1}$$

Where $\varepsilon_D = \varepsilon_1 + \alpha E_y^2$, ε_1 constituted the linear part of the dielectric constant, α was the nonlinear coefficient, ω is the operating frequency, and ω_p is the plasma frequency. The permeability of the nonlinear nonmagnetic left handed material was considered $\mu = 1$ [25, 35]. The electromagnetic field components are,

$$E = \left(0, E_y, 0\right)\ e^{ik_0(\beta x - ct)}, \tag{2}$$

$$H = \left(H_x, 0, H_z\right)\ e^{ik_0(\beta x - ct)}, \tag{3}$$

Substituting equations (2) and (3) into Maxwell's equations yield the nonlinear differential equation satisfies the nonlinear nonmagnetic NPM slab

$$\frac{\partial^2 E_y}{\partial z^2} - k_0^2\left(\beta^2 - \varepsilon_{DD} - \alpha E_y^2\right)\ E_y = 0, \tag{4}$$

where, $\varepsilon_{DD} = \varepsilon_1 - \dfrac{\omega_p^2}{\omega^2}$

The solution of the nonlinear differential equation (4) has the following form [35]

$$E_{y1} = (k_1/k_0)\ (2/\alpha)^{1/2} \sec h\left(k_1(z - z_0)\right) \tag{5}$$

Where z_0 is the position of the maximum of the field component in the nonlinear cover, and $k_1 = k_0\sqrt{\beta^2 - \varepsilon_{DD}}$. The magnetic field components in the NPM layers are:

$$H_{x1,3} = i\left(k_1^2/\omega\mu_0 k_0\right)\ (2/\alpha)^{1/2} \sec h\left(k_1(z - z_0)\right)\tanh\left(k_1(z - z_0)\right), \tag{6}$$

$$H_{z1,3} = -(k/\omega\mu_0)E_{y1} \tag{7}$$

In ferrite region the magnetic fields in the ferrite slab [21] were:

$$H_{z2} = k\left(Ae^{kz} + Be^{kz}\right) \tag{8}$$

$$H_{x2} = -ik\left(Ae^{kz} + Be^{kz}\right) \tag{9}$$

$$B_z = \mu_0 k\left[(\mu + vs)Ae^{kz} - (\mu - vs)Be^{-kz}\right] \tag{10}$$

$$E_{y2} = (\omega/k)B_x \tag{11}$$

where,

$$\mu = \mu_B\left[1 + (\omega_0\omega_m)/\left(\omega_0^2 - \omega^2\right)\right], \tag{12}$$

$$\nu = \mu_B\left[(\omega\omega_m)/\left(\omega_0^2 - \omega^2\right)\right], \tag{13}$$

Where $\omega_0 = \gamma\mu_0 H_0$ where H_0 is magnitude of the dc biasing magnetic field applied in the y direction and $\gamma = ge/2mc$ is the gyromagnetic ratio where *g* is the *g*-factor which is a measure of the strength of the spin-orbit coupling, e is the electronic charge c is the speed of light, and *m* is the mass of the electron, μ_B is the optical magnon permeability, $\omega_m = \gamma\mu_0 M_0$ where M_0 is the dc saturation magnetization, and $S = \pm 1$ is for forward and backward propagation respectively [22-23].

The dispersion relation could be found by matching the field components at the interface, $z = 0$, *and* $z = t$, which gives

$$e^{-2kt} = Z\ \frac{N(\mu + \nu\, s) + 1}{N(\mu - \nu\, s) - 1} \tag{14}$$

where

$$k = k_0\beta\ ,\ Z = \frac{R\,(\mu - \nu s) + 1}{R\,(\mu + \nu s) - 1}$$

Where $N = (k_1 / k)\ \tanh(k_1(t - z_0))$ and $R = (k_1 / k)\tanh(k_1 z_0)$

2.2: Power Flow

The power flux of the waves propagating in the *x*-direction is given by

$$P = \frac{1}{2}\int \left(E \times H^*\right)\ dz = \frac{1}{2}\int E_y H_z dz = P_{1NPM} + P_{Ferrite} + P_{2NPM} \tag{15}$$

$$P_{1NPM} = -\frac{1}{2}\left(kk_1 / k_0^2 \omega\mu_0\right)\left(2/\alpha_1\right)\left(u + 1\right)$$

$$P_{Ferrite} = \frac{1}{2}\omega\mu_0 kB^2\left[(\mu + \nu s)\left(e^{2kt} - 1\right)/2k + 2Z\nu st + (\mu - \nu s)\left(e^{-2kt} - 1\right)/2k\right]$$

$$P_{2NPM} = \frac{1}{2}\left(kk_1 / k_0^2 \omega\mu_0\right)\left(2/\alpha_1\right)\left(1 - \tanh\left(k_1\left(t - z_0\right)\right)\right)$$

where *u* is the nonlinearity, and

$$B = \left(k_1 / k_0\right)\left(2/\alpha\right)^{1/2}\left(1 - u^2\right)^{1/2} / \left(2\mu e^{-kt}\right)\left[\left(k_1 / k\right)u\left(\mu + \nu s\right) - \left(1/\omega\mu_0\right)\right]$$

Thus P_{1NPM} $P_{Ferrite}$ and P_{2NPM} stand for the power flux in the nonlinear nonmagnetic NPM, Ferrite, and nonlinear nonmagnetic NPM respectively, and $u = \tanh(kz_0)$.

3. Numerical Results and Discussion

The dispersion relation, equation (14), has been solved numerically (by using Maple program version 12, 2008) to calculate the complex effective wave index β as a function of the angular frequency ω, and the power flux for the structure under investigation. The parameters of the nonlinear nonmagnetic NPM and the gyromagnetic ferrite were adjusted such that the parameter ε_{eff}^{NL}, was negative in the same frequency range, which is located between $4.2-5.8\ GHz$. The parameters for the nonlinear nonmagnetic NPM and the gyromagnetic ferrite are: $\mu_B = 1.23$, $\alpha = 1.55\times10^{-10} m^2 V^2$, $\varepsilon_1 = 2.5$ $\mu_0 H_0 = 0.1T$, $\omega_P = 3\pi GHz$, $\omega_0 = 10.21 GHz$ $\mu_0 M_0 = 0.1750T$, $\gamma = 1.72\times10^{11} S^{-1} T^{-1}$ and, [7, 8]. In figure 2a, there plotted the effective refractive index versus the frequency range at $u = 0.25$ for $S = 1$. The effective refractive index decreases with ferrite's thickness increase and with the frequency increase. The slope of the dispersion curves represented the group velocity [25]. The slope of the dispersion curves was negative and depended upon ferrite's slab thickness and the operating frequency. This meant that the structure behaves like LHM. In figure 2b, there plotted the effective refractive index versus the frequency range at $u = 0.75$ for $S = 1$. There noticed a drastic change in the structure behavior since the effective refractive index in the structure was negative, a matter which meant that the structure at those operating conditions behaves like LHM, with positive slope of the dispersion curves. There noticed that there was no physical solution for $S = -1$.

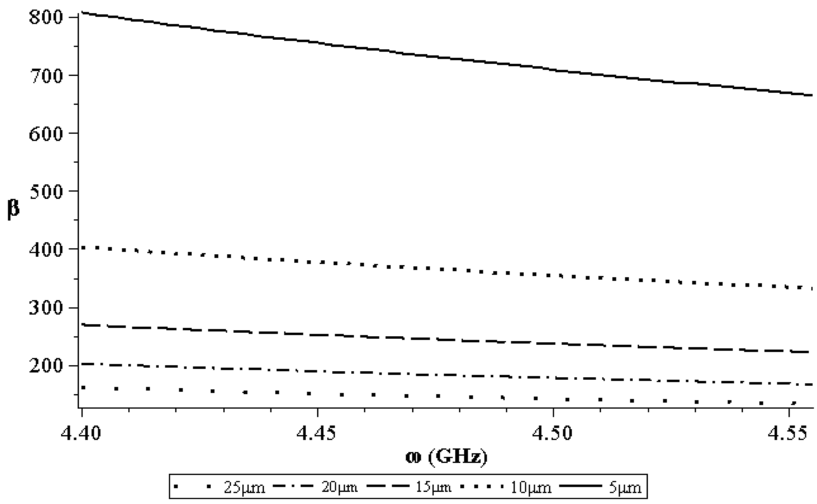

Figure 2.a

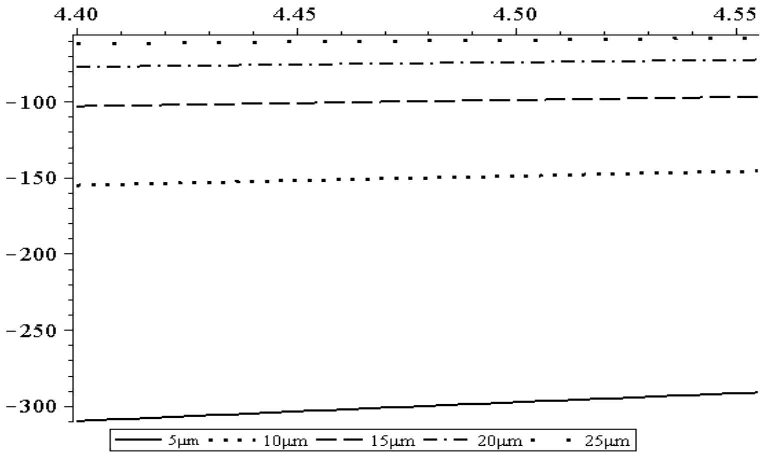

Figure 2.b

***Figure 2**: The effective refractive index versus the angular frequency at S=1 and nonlinearity **a.** u = 0.25 and **b.** u = 0.75 for different ferrite thickness, see the figure legends.*

In figure 3, we plot the effective refractive index versus the optical nonlinearity, u, at $5\,GHz$ operating frequency. It is noticed that the effective refractive index increases with optical nonlinearity increase for all thickness, but at a certain value of nonlinearity, $u = 0.57$, the effective refractive index flips to negative values. At low nonlinearity values the effective refractive index slope is positive which indicates that the structure behaves like right hand material, RHM. On the contrary, when the nonlinearity exceeds the 0.57 the slope of the curves is negative and the value of the effective refractive index is negative also, which is the behavior of the left handed materials. Thus controlling the nonlinearity we can control the behavior of the structure. In this structure, we can switch from on class of material to another by changing the electric field amplitudes, which induces lower/higher values of nonlinearity. This structure might be used in designing miniaturized Antennas and Planar Bandpass Filters [36]. Also, this structure can be used as microwave coupler since there is no physical solution in the Filters effect might be used in devices that the change between LHM to RHM is needed [15].

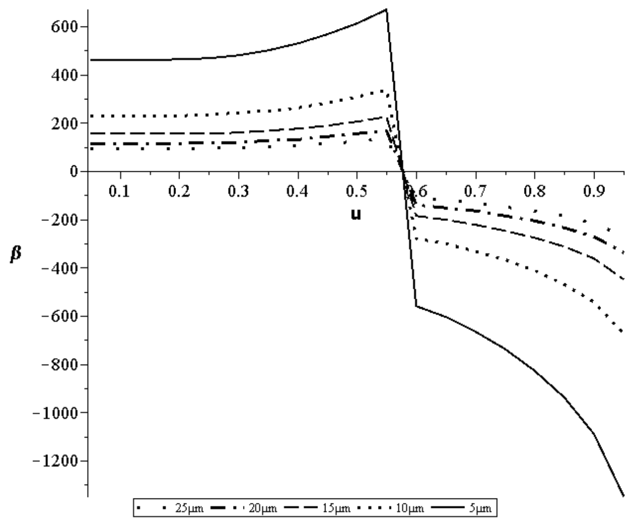

Figure 3: *The effective refractive index versus the nonlinearity at* $\omega = 5\ GHz$ *for different ferrite thicknesses.*

Figure 4 shows the normalized power flow, P/P_0, where $P_0 = 1/2\alpha\varepsilon_0\omega$, versus the operating frequency at optical nonlinearity $u = 0.25$ and $u = 0.75$ for forward propagation, $S = 1$. The power flow decreases with ferrite's slab thickness increase. At low nonlinearity values the power flow changes very slowly in the operating frequency range, figure 4.a. For high nonlinearity values there is a considerable change in power flow with the ferrite thickness and with the operating frequency, figure 4.b.

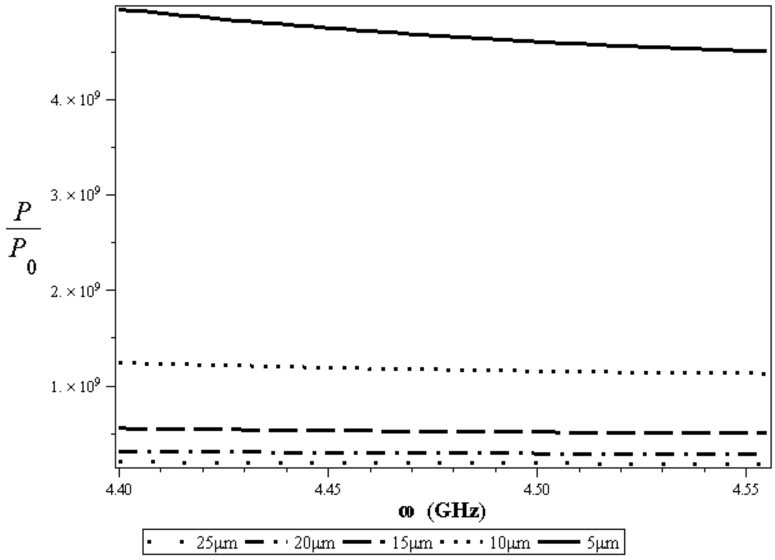

Figure4.a

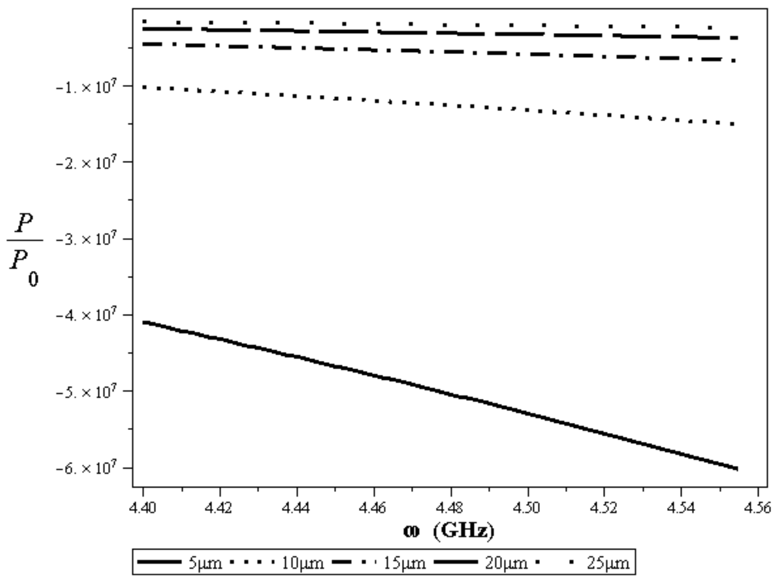

Figure 4.b

Figure 4: *The normalized power flux versus the operating frequency at S=1 and optical nonlinearity* ***a.*** $u = 0.25$ *and* ***b.*** $u = 0.75$ *for different thickness.*

Figure 5, shows the normalized power versus the effective refractive index with optical nonlinearity and S=1 at $5GHz$ operating frequency. Power flow was dependent on ferrite's slab thickness and optical nonlinearity. The power flow decreases with thickness increase.

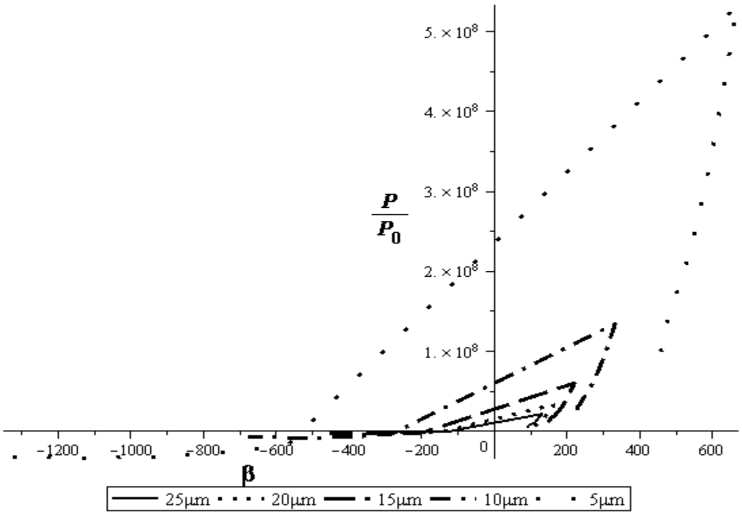

Figure 5: *The normalized power flux versus the effective refractive index at* $\omega = 5$ GHz*, with optical nonlinearity and different ferrite thicknesses.*

Figure 6, shows the normalized power versus the optical nonlinearity at $\omega = 5\ GHz$ operating frequency. The power flow increases with nonlinearity increase and then at $u = 0.57$ the power flow falls down to negative values. Again, this behavior assures that the structure behaves like RHM when the nonlinearity is less than 0.57 and behaves like LHM when the nonlinearity is greater than this value.

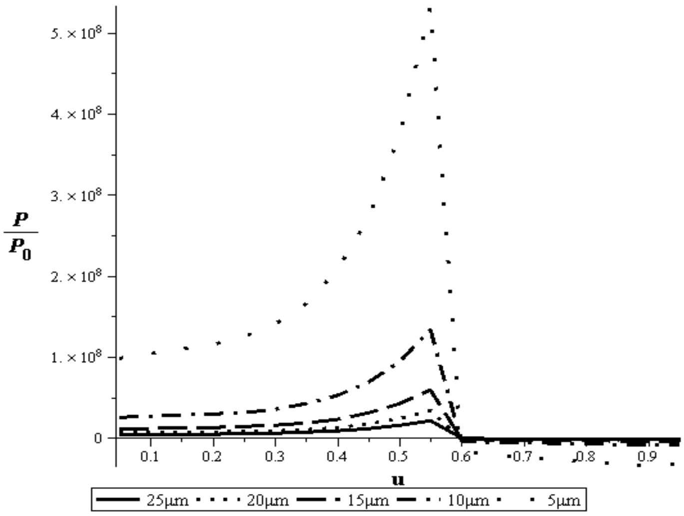

Figure 6: *The normalized power flux versus the effective nonlinear wave index at ω = 5 G Hz, and different thicknesses.*

4. Conclusion

A design of a three layer waveguide has been introduced, which is a ferrite layer sandwiched between two thick layers of nonlinear nonmagnetic negative permittivity material (NPM). A dispersion relation for TE surface waves has been derived and numerically investigated. We found that the wave effective refractive index decreases with frequency increase at certain range of frequency: the structure behaves like a RHM with positive effective refractive index and positive group velocity at low optical nonlinearity values; and like LHM with negative effective refractive index and negative group velocity at high optical nonlinearity values. The power flow for forward propagation, $S=1$, is inversely proportional to ferrite slab thickness; the power flow decreases with slab thickness increase. The nonlinearity affects the power flow drastically: the power flow increases by increasing the nonlinearity for all thicknesses and then peaks and flips at $u=0.57$, which ensures that the structure changes its behavior from RHM to LHM. Those promising characteristics could be used in future in designing some microwave-optoelectronic devices, couplers, antenna, and microstrip resonators.

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