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High-efficiency tunable T-shaped beam splitter based on one-way waveguide

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Abstract. Power splitters have been widely studied in the fields of radio frequency and integrated photonics, however, conventional splitters generally suffer with poor transmission and limited bandwidth. Here we propose a novel tunable T-shaped power splitter utilizing one-way waveguide that is composed by the yttrium-iron-garnet (YIG)-air-metal configuration with one static magnetic field applied. We show that the transmission efficiency of such a splitter reaches 100% in the lossless case due to the suppression of reflection by the one-way waveguide. By introducing a defect in the junction area, the splitting ratio of the splitter can be gradually tuned by varying the external magnetic field, and large operation bandwidth can be achieved for a given splitting ratio. Our results presented here focus on the radio frequency, and the concept can easily be applied to the photonic area.

Keywords: Power splitter, one-way propagation, surface plasmons, waveguide

1. Introduction

Power splitter is one of the key elements in radio technology [1, 2, 3] and integrated photonics [4, 5, 6, 7], and has been widely used for many applications including interferometers [8], optical switches [9, 10], and multiplexing devices [11, 12]. T-splitters and Y-splitters are the commonly used power splitters [13, 14, 15, 16]. For these splitters, two fundamental issues of their design are tunable splitting ratio and high transmission efficiency. Having multimodes in the junction often leads to mode-mixing problems, giving the rise to the mode-match problem with respect to the input and output modes [15]. Therefore, significant reflection at the junction is normally observed. To improve the transmission of the splitters, lots of work have been performed by developing better junctions [17, 18]. For a unequal power splitter, the modification of the junction structure naturally results in the variation of the splitting ratio, however giving rise to the big challenge for the design of tunable devices.

Recently, many groups have proposed an alternative and effective way to improve the transmission efficiency of splitters by using one-way electromagnetic (EM) waveguide [19, 20], which was firstly proposed as analogues of quantum Hall edge states in photonic crystals (PhCs) [21, 22, 23]. The mode supported by the one-way EM waveguide can only propagate in one direction, and is immune to backscattering at discontinuities or bends because of the absence of a back-propagating mode [24, 25, 26, 27, 28, 29]. The one-way waveguide enables us to deal with the issue of the transmission efficiency [30] in the design of the power splitter. Based on a gyromagnetic material, i.e., yttrium-iron-garnet (YIG), different PhC T-splitters incorporating the concept of one-way waveguide have been proposed at microwave frequencies. It has been shown that the transmission efficiency is always 100% in the lossless case [19, 20]. Moreover, these splitters exhibit high-efficiency and reflection-free even with obstacles, which would be impossible for the regular PhC splitters studied before. However, in those devices, two or more uniform dc magnetic fields with different directions are required. More recently, we have reported a robust one-way waveguide formed by bulk gyromagnetic YIG [31]. This system supports not only one-way surface magnetoplasmons (SMPs) but one-way regular modes, which are confined by total internal reflection. These one-way regular modes can also be immune to backscattering. Compared to one-way PhC modes, the one-way waveguide we proposed in Ref. [31] is simple in geometry and the design is more robust in mechanism.

In this paper, we propose a tunable T-shaped splitter, where the input and output waveguides are composed by our proposed one-way waveguide i.e., YIG-air-metal configuration with one static magnetic field applied. Here only one external magnetic field is needed. We show that the device possesses high efficiency and its tunable splitting ratio by varying the external magnetic field when a defect is introduced in the junction of the splitter. Finally broad-band operation with high-efficiency is also presented.

2. Dispersion Property of One-way Waveguide

The one-way waveguide is formed by the YIG-air-metal configuration, see the inset of Fig. 1(b), where the thickness of the air layer is denoted by d , and where the thickness of the metal/YIG is semi-infinite. The magnetized YIG is gyromagnetic anisotropic with permittivity $\varepsilon_m (= 15)$ and permeability tensor μ_m , which takes the form [32]

$$\vec{\mu}_m = \begin{bmatrix} \mu_1 & -i\mu_2 & 0 \\ i\mu_2 & \mu_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (1)$$

with

$$\mu_1 = 1 + \frac{\omega_m(\omega_0 - iv\omega)}{(\omega_0 - iv\omega)^2 - \omega^2},$$

$$\mu_2 = \frac{\omega_m\omega}{(\omega_0 - iv\omega)^2 - \omega^2},$$

where ω is the angular frequency, ω_m is the characteristic circular frequency, v is the damping coefficient, and $\omega_0 = 2\pi\gamma H_0$ (γ is the gyromagnetic ratio) is the precession angular frequency. Such a three-layer structure can support both SMPs and regular modes, whose dispersion relations are given by [31]

$$\alpha_r\mu_v + (\alpha_m + \frac{\mu_2}{\mu_1}k) \tanh(\alpha_r d) = 0, \quad \text{SMP} \quad (2)$$

$$p\mu_v + (\alpha_m + \frac{\mu_2}{\mu_1}k) \tan(pd) = 0, \quad \text{regular mode}, \quad (3)$$

where k is the propagation constant, $\alpha_m = \sqrt{k^2 - \varepsilon_m\mu_v k_0^2}$ with $\mu_v = \mu_1 - \mu_2^2/\mu_1$ (the Voigt permeability), $p = \sqrt{k_0^2 - k^2}$, and $\alpha_r = \sqrt{k^2 - k_0^2}$ with $k_0 = \omega/c$ being the vacuum wavenumber. The linear terms of k in Eqs. (2) and (3) indicate that both SMPs and regular modes supported by the YIG-air-metal structure are nonreciprocal. Figure 1(a) shows the dispersion relations for the regular mode (the red solid line) and SMPs (the blue dashed lines), which lie up and below of the light cone (the black dot-dashed lines), respectively. Here we assume the YIG medium to be lossless ($v = 0$) with $\varepsilon_m = 15$ and $\omega_m = 10\pi \times 10^9$ rad/s ($f_m = 5$ GHz), and ω_0 is set at $0.5\omega_m$, which is equivalent to $H_0 = 893$ G. In this work, the thickness of the air layer is fixed as $d = 0.05\lambda_m$, i.e., $d = 3$ mm. In Ref. [31], we have shown that the dispersion relation and bandwidth for the one-way propagation are affected by the thickness of the dielectric layer d . Here we choose $d = 3$ mm which provides the largest bandwidth. The bands of two types of modes are connected at the light lines ($\omega = c|k|$), as shown in Fig. 1(a). The uppermost and lowest shaded areas represent zones of bulk modes ($k^2 < \varepsilon_m\mu_v k_0^2$) supported by the YIG, whose band gap ranges from $\omega_a = \sqrt{\omega_0(\omega_0 + \omega_m)}$ to $\omega_b = \omega_0 + \omega_m$. The middle shaded area represents the bandwidth exhibiting robust one-way propagation (ROWP). The lower limit of ROWP is equal to $\omega_{sp} = \omega_0 + \omega_m/2$, i.e., the asymptotic frequency of SMP when $k \rightarrow -\infty$, and the upper limit is ω_b associated with the lower limit of the second bulk-mode zone in YIG. As seen in Fig. 1(a), the ROWP band ranges from ω_m to

Figure 1. (Color online)(a) Dispersion relations of SMPs and regular mode for $H_0 = 893$ G in the YIG-air-metal structure. The uppermost and lowest shaded areas represent the band structure of bulk modes in the YIG, and the middle one represents the ROWP region for the structure. (b) ROWP bands for various H_0 values. The solid lines from the top to bottom represent $H_0 = 1100$, 893, and 300 G, respectively. The inset shows the schematic of the YIG-air-metal structure, where the thickness of air layer is denoted as $d = 3$ mm.

$1.5\omega_m$, equivalent to the frequency region $[5, 7.5]$ GHz. In this window, both SMPs and the regular mode are allowed to propagate only in one direction, and they are immune to backscattering at imperfections because of the absence of a back-propagating mode in the system.

The influence of the external magnetic field H_0 on the ROWP band is further investigated, see Fig. 1(b). As mentioned above, the ROWP band ranges from $\omega_{sp} = \omega_0 + \omega_m/2$ to $\omega_b = \omega_0 + \omega_m$, and the bandwidth for the ROWP is governed by $\Delta\omega = \omega_m/2$, showing independence to the external magnetic field. However, both the lower and upper limit for the ROWP band shift up when increasing of H_0 . As an example, we analyze different H_0 values: $H_0 = 1100$, 893, and 300 G, see the solid lines from top to bottom in Fig. 1(b). For a given frequency, the propagation constant (k) of the one-way mode changes as a function of H_0 , indicating that the guiding property of the one-way mode is strongly affected by the external magnetic field.

Figure 2. (Color online) Schematic of tunable T-shaped power splitter, where the YIG rod (with radius of r) in the junction region is used to tune the splitting ratio.

3. Characteristic of the high-efficiency splitter

The proposed T-shaped splitter based on one-way waveguides is illustrated in Fig. 2, where the input and output channels are all composed by the YIG-air-metal waveguide. For simplicity, here we consider the device in the two dimensional case. In the ROWP range of the YIG-air-metal waveguide, the input channel supports no back-propagating mode, thus incident wave can be completely split into the output channels through the junction region. Therefore, such a splitter has a perfect transmission efficiency of 100% provided that the materials in the system are all lossless. However, due to the asymmetric configuration for two output channels, the splitting ratio is very limited if we do not introduce a defect in the conjunction region. To efficiently tune the splitting ratio between the two output channels, a YIG rod with radius of r is inserted in the junction region, where the center of the YIG rod is denoted by $C(x_c, y_c)$. When introducing the defect, the asymmetric configuration for two output channels makes it feasible to tune the splitting ratio by varying the external magnetic field.

To verify the tunability of the proposed splitter, we perform full-wave simulations with the aid of the commercially available finite element method (COMSOL Multiphysics), and we first investigate the splitting ratio of the device without introducing any defect in the junction, as seen in Fig. 3(b). To excite waves in the input channel, a linear electric current is placed at 1.5 mm above the YIG surface. Due to the nature of the one-way waveguide, the incident wave from the input channel can be totally coupled into the output channels. However, the asymmetric configuration for two output channels leads to very small energy of 0.031 in the output port 1, see Fig. 3(b), when $H_0 = 893$ G and $f = 5.6$ GHz. Our analysis also shows that the tunability as a function of the magnetic field for the structure without having the defect is also limited. We further explore the transmission properties of the power splitter when introducing the defect, as seen in Fig. 2. Note that the performance of the power splitter is strongly dependent on the size, position of YIG rod, and external applied magnetic field. We have

Figure 3. (Color online)(a) Transmission coefficients of the splitter assisted with the YIG rod as a function of H_0 . Simulated $\mathbf{E}$ amplitudes in the T-shaped power splitter without (b) and with (c) the YIG rod with the radius of 1.5 mm when $H_0 = 893$ G and $f = 5.6$ GHz.

systemically analyzed the property of the proposed device, and here we choose $r = d/2$, $x_c = 0$ mm and $y_c = 1.03$ mm as an example in order to achieve large bandwidth. The operation frequency is set to be $f = 5.6$ GHz, at which the input and output channels exhibit ROWP behaviour with magnetic field H_0 ranging from 300 G to 1100 G. Figure 3(a) illustrates the transmission coefficients η_1 (η_2), defined by the ratio of powers in the upper (lower) output channel to the input channel, when varying the magnetic field. With neglecting the loss of the materials, the total transmission ($\eta_1 + \eta_2$) is always unity due to ROWP feature. When introducing the defect, the transmission coefficients at two output channels can be strongly modified, by varying the magnetic field. As an example, $\eta_1 = 0.02$ and $\eta_2 = 0.98$ when $H_0 = 300$ G; whereas $\eta_1 = 0.96$ and $\eta_2 = 0.04$ for $H_0 = 1100$ G. One can find in Fig. 3(a) that η_1 monotonously increases with H_0 except in the small interval [802, 893] G. In this interval, there always exists a pair of H_0 values at which η_1 (as well as η_2) are the same. For example, $\eta_1 = \eta_2 = 0.5$ at both $H_0 = 893$ G and $H_0 = 802$ G, which are marked by A and A' in the figure. It is found that $\eta_1 = 0.65$ and $\eta_2 = 0.35$ when $H_0 = 979$ G (marked by B). Figure 3(c) show the simulated electric field amplitudes for the cases of $H_0 = 893$ G, where the incident wave is equally coupled into the output channels with the aid of the defect, i.e., $\eta_1 = \eta_2 = 0.5$. Note that the mode presented here refers to the regular mode mentioned above.

We further investigate the spectral characteristic of the power splitter with focus on the case of equal splitting. For $f = 5.6$ GHz, the equal splitting is reached in the two

Figure 4. (Color online) (a) η_1, η_2 and $\eta = (\eta_1 + \eta_2)$ as a function of f for $H_0 = 893$ G. (b) Transmission spectra in a frequency interval around 5.6 GHz for $H_0 = 893$ G and 802 G.

cases of $H_0 = 893$ G and 802 G, which are marked by A and A' in Fig. 3, respectively. Figure 4(a) shows the spectra of η_1 , η_2 , and $\eta (= \eta_1 + \eta_2)$ for $H_0 = 893$ G. Both η_1 and η_2 vary largely with f , but η is kept to be unity over the range $[5, 7.5]$ GHz, which is exactly associated with the ROWP band for the YIG-air-metal waveguide under $H_0 = 893$ G. The equal splitting's band, defined as within 2% error for a desired splitting ratio, is $[5.51, 5.65]$ GHz, as shown in Fig. 4(b). The η_1 spectrum for $H_0 = 802$ G (marked by A') is also calculated and presented in Fig. 4(b) for comparison. The spectra for the two cases are rather different, and the one for $H_0 = 893$ G has a relatively large bandwidth because the derivative $d\eta_1/df$ vanishes at $f = 5.6$ GHz. Note that the derivative $d\eta_1/dH_0$ also vanishes at $H_0 = 893$ for $f = 5.6$ GHz, as seen in Fig. 3(a). Evidently, η_1 as functions of both f and H_0 possesses an equilibrium point at $f = 5.6$ GHz and $H_0 = 893$ G, where $\eta_1/\eta_2 = 0.5/0.5$. This equilibrium point is beneficial to get a large bandwidth for the equal splitting.

The existence of the equilibrium point provides a promising way to achieve larger bandwidth for desired splitting ratio. For our proposed high-efficiency splitter, the equilibrium point (at a certain frequency) can also be attained for any unequal splitting

Figure 5. (Color online)(a) η_1 as a function of f for two unequal power splitters. The YIG rod is centered at $C(-0.05, 0.80)$ mm for $H_0 = 893$ G and at $C(0, 1.03)$ mm for $H_0 = 979$ G. For both the splitters, $\eta_1/\eta_2 = 0.65/0.35$ at $f = 5.6$ GHz. (b) η_1 and η_2 as functions of H_0 for $f = 5.6$ GHz. The YIG rod is located at $C(-0.05, 0.80)$ mm. (c) Simulated $\mathbf{E}$ amplitudes for the equilibrium point of $H_0 = 893$ G and $f = 5.6$ GHz when the YIG rod is centered at $C(-0.05, 0.80)$ mm.

by adjusting the position of the YIG rod. To show this, we consider an example of unequal splitting with $\eta_1 = 0.65$ and $\eta_2 = 0.35$. As seen from Fig. 3(a), this splitting

behaviour happens at $f = 5.6$ GHz and $H_0 = 979$ G (marked by B), and obviously, it is not an equilibrium point for $\eta_1/\eta_2 = 0.65/0.35$, because $d\eta_1/dH_0 \neq 0$ at $H_0 = 979$ G. In this case, it is found that $d\eta_1/df$ also does not vanish at $f = 5.6$ GHz, as shown in Fig. 5(a), where the η_1 spectrum is plotted for $H_0 = 979$ G. For $f = 5.6$ GHz, we analyze the dependence of η_1 on H_0 for different YIG-rod positions, and find that $d\eta_1/dH_0 = 0$, see in Fig. 5(b), appears at $H_0 = 893$ G when $x_c = -0.05$ mm and $y_c = 0.8$ mm (marked by B*). The η_1 spectrum for $H_0 = 893$ is also displayed in Fig. 5(a), and as expected, $d\eta_1/df$ vanishes at $f = 5.6$ GHz as well. Hence, the point of $f = 5.6$ GHz and $H_0 = 893$ G is an equilibrium point for $\eta_1/\eta_2 = 0.65/0.35$. But this equilibrium point is rather different from that (marked by A) in Fig. 3(a) in mathematics, the latter is a inflection point for the transmission coefficient η_1 (or η_2) as the function of f and H_0 . Clearly, the present equilibrium point marked by B* in Fig. 5(b) is a stationary point, where $\partial\eta_1/\partial f$ and $\partial\eta_1/\partial H_0$ also vanish. In contrast, the point B in Fig. 3(a) is not an equilibrium point, because $\partial\eta_1/\partial H_0$ as well as $\partial\eta_1/\partial f$ are nonzero. Evidently, there exist at least two kinds of equilibrium point for η_1 (or η_2), and this increases the possibility of the existence of equilibrium point for arbitrary splitting ratio. By searching for the equilibrium point, we here obtain a relatively larger bandwidth for the unequal splitting of $\eta_1 = 0.65$ and $\eta_2 = 0.35$. The large bandwidth for a desired splitting ratio (under a certain external magnetic field) is of importance for pulse signal processing. Figure 5(c) shows the simulated electric amplitudes for the equilibrium point of $f = 5.6$ GHz and $H_0 = 893$ G. The YIG rod is located at C(−0.05, 0.80) mm. As expected, the field amplitudes in the upper output channel are apparently stronger than those in the lower one, which is obviously different from the case of equal splitting in Fig. 3(c).

If signals to deal with are monochrome or quasi-monochrome, large operation range can be easily obtained for our proposed splitter by tuning the external magnetic field. Evidently, in this situation, the operation range for a certain splitting ratio is only determined by the ROWP behaviour of the input channel. The value of H_0 versus frequency for $\eta_1/\eta_2 = 0.5/0.5$ is evaluated and plotted as the solid line in Fig. 6, where $x_c = -0.05$ mm $y_c = 0.8$ mm, and the other parameters of the system are the same as in Fig. 1. The operation range is from 4 GHz to 7 GHz, while H_0 is tuned from 277 G to 1265 G. One-way propagation is also available for the whole frequency range. More interestingly, the value of H_0 almost increases linearly with the frequency in the range [4, 7] GHz, as shown in Fig. 6. This situation also happens for other splitting ratio. To show this, another example of unequal splitting with $\eta_1 = 0.65$ and $\eta_2 = 0.35$ is also displayed as the dashed line in Fig. 6, where $x_c = 0$ mm $y_c = 1.03$ mm. Here the operation band ranges from 4 GHz to 7 GHz, when H_0 is tuned from 443 G to 1450 G. In the region [4, 7] GHz, H_0 versus f for $\eta_1/\eta_2 = 0.65/0.35$ is similar to the first case as expected. For both examples, the transmission efficiency of 100% is preserved.

Figure 6. (Color online) Splitting ratio versus H_0 and f for the proposed splitters. The solid and dashed lines represent the equal splitting and unequal splitting with $\eta_1/\eta_2 = 0.65/0.35$, respectively. The YIG rod lies at $C(-0.05, 0.80)$ mm for $\eta_1/\eta_2 = 0.5/0.5$ and at $C(0, 1.03)$ mm for $\eta_1/\eta_2 = 0.65/0.35$. The other parameters are the same as in Fig. 1.

4. Conclusions

We have proposed and studied novel tunable T-shaped splitters utilizing one-way waveguide, where the one-way waveguide is built on the YIG-air-metal configuration with one static magnetic field applied. The guiding properties of the YIG-dielectric-metal structure has been analyzed, and the waveguide exhibits a robust one-way propagation over a large frequency range. The transmission efficiency of the splitter is 100% over the ROWP range provided that the materials in the system are lossless. When introducing the defect in the junction, the splitting ratio is strongly modified due to the asymmetric feature of two output channels. Our results further illustrate that the splitting ratio of the splitter can be gradually tuned by varying the applied magnetic field. The power splitter proposed here works on radio frequency in a two-dimensional configuration, and it can be easily extended to a three-dimensional structure and to the subject of integrated photonics.

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