Magnetically Tunable Resonant Phase Shifters for UHF Band

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This paper presents a new type of magnetically tunable phase shifter. The shifter has the structure of microstrip bandpass filter on a substrate containing magnetic material whose magnetic permeability is controlled by magnetic field due to ferromagnetic resonance. The phase shifter's operation is based on the fact that phase shift in a bandpass filter changes with tuning of its central frequency. Two types of devices were designed and fabricated for the UHF band. One of them has a five-layer NiFe film as an active medium and demonstrates a figure of merit of 40°/dB achieved already at 20 Oe of the controlling magnetic field in 10% of the relative operational bandwidth. The second device with YIG ferrite as an active medium gave 360° tunable phase shift in 5% operational bandwidth that corresponds to the figure of merit of 150°/dB (3.1°/dB · Oe).

***Index Terms*—Ferrite, microstrip structure, microwave, tunable phase shifter.**

I. INTRODUCTION

TUNABLE microwave phase shifters (PSs) are among the most important components in phased array antennas [1], [2]. With the continuous development of radio electronics, requirements of PSs permanently increase, especially with regard to their performance, miniaturization, and manufacturability. For the moment, the best combination of the characteristics may be achieved using strip and microstrip transmission lines in designing [3]–[5]. Such device, as a rule, is a transmission line whose electrical length is tuned by electric or magnetic field due to it being fulfilled on a substrate with controllable permittivity (ε) or permeability (μ). An important parameter of a tunable PS is the value of the maximal phase shift. In the traditional approach, the only way to improve it is to make the line longer, i.e., to make the device larger. This is because, nowadays, materials characterized by large tunable change in magnetic permeability on microwaves do not exist. So, new approaches in designing tunable PSs are desirable. One of them, named resonant, was proposed in [6] and [7] and developed in a number of works [8], [9]. The approach is based on a simple idea that in the filter's passband, its phase response is linear and by filter tuning this response shifts along the frequency axis without changing its slope. Thus, in some band the tuned change of the phase occurs. It should be noted that the filter is resonator based. Obviously, the proposed method provides an opportunity to design multifunctional devices, because the PSs simultaneously perform the function of bandpass filter. In some cases, this can greatly simplify the circuits by eliminating the need to further use frequency-selective devices.

In principle, the resonator used in the PS may be of any construction, but it is most convenient to use stripline or microstrip ones. On their base one can design miniature PSs with high figure of merit [10] operation at frequencies from UHF band to Ka band. In this paper, we present the results of an investigation aimed to design resonant microstrip phase shifters using a magnetic media controlled by magnetic field as a part of the substrate.

This paper is organized as follows. In Section II, we give the basics of the resonant approach and compare the estimated results that can be achieved with matched line PS and resonant PS. In Section III, we present the results of measurements of magnetic properties for the active media used in the designed PS, particularly multilayer magnetic film and YIG ferrite. Two PSs were designed and fabricated using multilayered thin magnetic film and ferrite substrate. Their design and measured responses are presented in Section IV. The results of the investigation are summarized in Section V.

II. RESONANT METHOD

It is well known that the slope of phase response for an unmatched segment of transmission line dramatically increases near its resonance frequency in comparison with the slope relating to the case of a matched segment. This is a key factor in the method. Let us consider a system of coupled resonators that in fact is a bandpass filter. In Fig. 1, the solid line denotes the typical frequency and phase responses of a bandpass filter with central frequency f_0 and bandwidth Δf. If one changes the central frequency of the filter by an offset δf, which does not exceed the bandwidth Δf (dashed line in Fig. 1), it is easy to see that a band $W \approx \Delta f - \delta f$ exists inside the original passband of the filter where the phase of a signal changes by the value equal to $\Delta\varphi$. So a tunable bandpass filter can perform a function of tunable (controllable) PS with an operating bandwidth of W.

The expression for estimating the value of tunable phase shift for resonant structure was presented in [7]

$$\Delta\varphi = N \times \text{arctg}(-4Q\delta) \tag{1}$$

where N is the number of resonators in a device, Q is loaded quality factor of resonators, and $\delta = \delta f/(2f_0)$ is relative frequency detuning.

The detuning δ is determined by the value of operating bandwidth of the PS and is limited by transmission bandwidth of the device. For example, for a resonant PS with relative operation bandwidth 0.1 (10%), based on bandpass filter with fractional bandwidth 0.2 (20%) the maximum relative frequency shift will be 0.1, which corresponds to $\delta = 0.05$.

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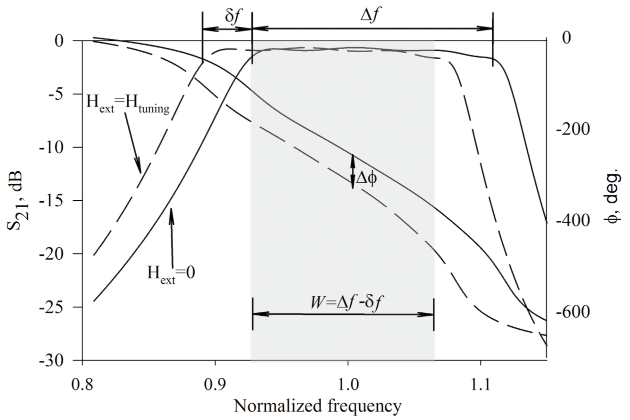

Fig. 1. Typical frequency and phase responses of a bandpass filter (solid lines) and those shifted on δf (dashed lines). Gray area: operational band of the PS.

At the same time, the bandpass filter with fractional bandwidth 20% has the loaded quality factor $Q \approx 1/0.2 = 5$ (whereas it may be formed by resonators with unloaded $Q > 100$). So, according to (1), the maximum value of the tunable phase shift $\Delta\varphi$ for such device will be 45° per resonator. To obtain 180° phase shift, one needs to use four resonators in the device.

Parasitic modulation of a signal and termination mismatch occurring on the PS tuning will be negligible for resonant PSs as it operates inside the bandpass where the frequency response is uniform.

Let us compare differential phase shifts yielded by the resonant PS and the one based on matched transmission line. Both microstrip structures are designed on a substrate with controllable μ. The resonance frequency of microstrip transmission line of the length l is

$$\omega_0 = \frac{\pi c}{l\sqrt{\varepsilon\mu}} \tag{2}$$

where l is the length of the line, c is velocity of the light in vacuum, ε is effective dielectric permittivity of the substrate, and μ is its effective magnetic permeability.

An oscillation phase-frequency response near the resonance is determined by [11]

$$\varphi = \operatorname{arctg}\left(\frac{1}{Q}\cdot\frac{\omega/\omega_0}{1-(\omega/\omega_0)^2}\right) \tag{3}$$

where Q is the quality factor of the resonance, and $\omega = 2\pi f$ and $\omega_0 = 2\pi f_0$ are the circular frequency of the oscillation and the resonance frequency, respectively. Then, substituting (2) in (3) and differentiating the latter, we get the tunable phase shift corresponding to the tuned change in effective permeability of the substrate $d\mu$

$$d\varphi = \frac{Q\omega}{2\omega_0\mu}\cdot\frac{1+(\omega/\omega_0)^2}{Q^2[1-(\omega/\omega_0)^2]^2+(\omega/\omega_0)^2}\,d\mu. \tag{4}$$

As PS operates near the initial resonant frequency of the structure, $\omega \approx \omega_0$ and we can write

$$d\varphi \approx \frac{Q}{\mu}d\mu. \tag{5}$$

In the case of matched microstrip transmission line of the same length l, the phase shift of the signal that passed the line is proportional to its electrical length

$$\varphi = \frac{2\pi l\sqrt{\mu\varepsilon}}{\lambda} \tag{6}$$

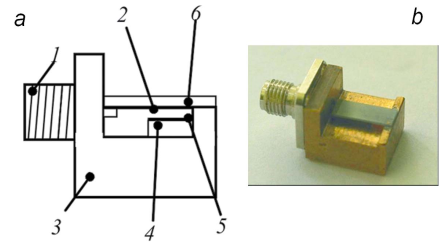

Fig. 2. (a) and (b) Measuring cell for thin film magnetic permeability characterization. 1: SMA connector. 2: inverted stripline. 3: grounded plate. 4: thin film substrate. 5: magnetic thin film. 6: alumina substrate.

where λ is the wavelength in vacuum. Differentiating the latter, we get

$$d\varphi = \frac{\pi l}{\lambda\sqrt{\mu\varepsilon}}d\mu. \tag{7}$$

If $\omega \approx \omega_0$, then $\lambda \approx 2l\sqrt{\mu\varepsilon}$ and differential phase shift in the matched line based PS is

$$d\varphi \approx \frac{\pi}{2\mu}d\mu. \tag{8}$$

When comparing (5) and (8), one can see that the differential phase shift in resonant PS is around Q times higher than in PS based on matched line under the same conditions.

III. Magnetic Material Characterization

A. Thin Magnetic Film

It is well known that ferrite-based tunable devices require high magnitude of a bias magnetic field for operation. Thin magnetic metallic films can be a possible alternative to ferrite in the case of chip-integrated device, but a single-layer thin film has a very low filling factor that incredibly reduces the effective magnetic permeability of the substrate. Usage of multilayered thin films is one of the ways of solving the problem and achieving the value of figure of merit comparable with that for ferrite-based planar PS.

In this paper, five-layered magnetic thin film $(Ni_{70}Fe_{30}/SiO)_5$ was used, in which 500 Å magnetic layers were isolated from each other by 5000 Å of dielectric layer. The magnetic film was produced by vacuum deposition on 0.5 mm glass substrate. The glass substrate had size 10 mm × 22 mm.

Characterization of the film was made by means of ferromagnetic resonance (FMR) using local FMR spectrometer [12], [13] operating at 1034 MHz. The angular dependence of FMR field in the film gives us the value of saturation magnetization = 13 900 Gs; anisotropy field $H_a = 8.7$ Oe; linewidth of uniform FMR $\Delta H = 8.8$ Oe; and directions of easy and hard axes in the plane of the film.

The measurement of magnetic permeability for the film was performed by means of measuring cell based on $\lambda/4$ short-circuited inverted 50 Ω stripline presented in Fig. 2 in accordance with the method presented in [14]. The stripline with a length of 10 mm and fulfilled on 0.5 mm alumina substrate was suspend at 0.5 mm above a grounded plate. The stripline by the open end was connected to the network analyzer R&S ZVL13 (not shown in Fig. 2).

The value of magnetic permeability on each frequency can be calculated through the reflection coefficient measured in

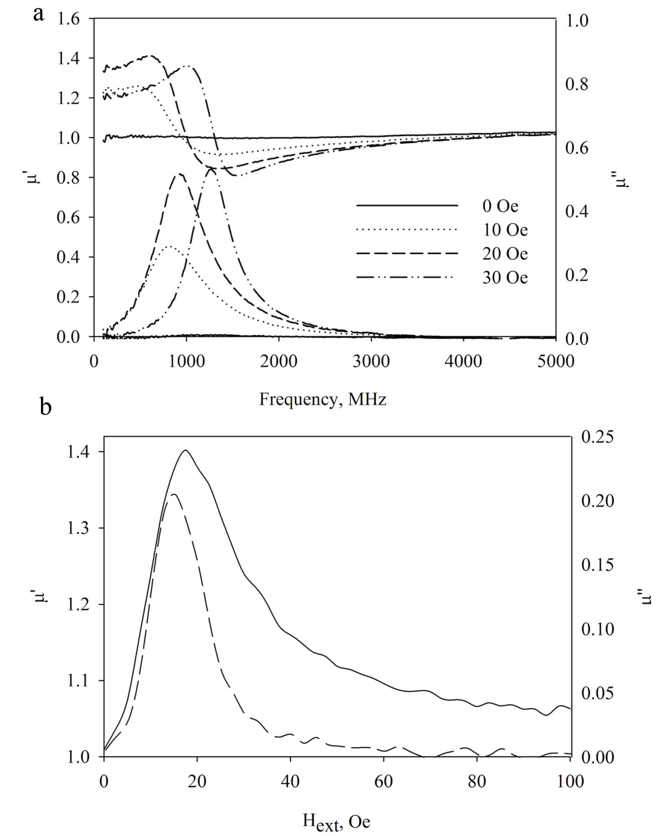

Fig. 3. (a) Frequency dependence of magnetic permeability for five-layer NiFe thin magnetic film for the various values of magnetic field (the upper curves correspond to μ', the lower ones to μ''). (b) Field dependence of magnetic permeability (solid line: μ', dashed line: μ'') measured at 500 MHz.

three cases: 1) empty cell S_{11}^{empty}; 2) cell filled with clean glass substrate S_{11}^{sub}; and 3) cell with the studied film S_{11}^{film} as

$$\mu = \left(\frac{ic \ln\left(-S_{11}^{\text{sub}}\right)}{2\omega l_{\text{sample}}\sqrt{\varepsilon^{\text{sub}}}} - \frac{\sqrt{\varepsilon^{\text{empty}}}l_{\text{empty}}}{l_{\text{sample}}\sqrt{\varepsilon^{\text{sub}}}} \right)^2 \quad (9)$$

where l_{sample} and l_{empty} are the lengths of the line segment filled with the film and without the film, respectively; ω is frequency; c is light velocity; $\varepsilon^{\text{empty}}$ is permittivity of the substrate calculated in the case of the empty cell for strip line; and ε^{sub} is permittivity of the substrate segment filled with the glass substrate without the film for microstrip line. It should be mentioned that all permittivities are effective.

In Fig. 3(a), the frequency dependence of magnetic permeability is presented for the different strengths of bias field applied in the direction of the film easy axis. It can be found that for the investigated five-layer NiFe thin film the maximum value of the magnetic permeability was obtained at 20 Oe of the bias field. The result is confirmed by Fig. 3(b) where the field dependence of μ is presented. Thus, the maximum value of $\mu = 1.4$ is achieved at 20 Oe for the frequency about 500 MHz. With the help of these data, we have chosen the operating frequencies range of the designed PS.

B. YIG Ferrite

For the current investigation, a commercial ferrite was chosen, designed to operate at frequency around 1 GHz. The declared properties of the ferrite were as follows: 1) saturation magnetization $4\pi M_s = 1200$ Gs; 2) coercive force field $H_c = 1$ Oe; 3) dielectric constant of the substrate $\varepsilon = 14.6$; and 4) dielectric loss $\tan\delta = 2 \times 10^{-4}$. The size of the ferrite plate was 9.5 mm × 19.3 mm × 0.5 mm.

The effective magnetic permeability of the ferrite was $\mu = 13$.

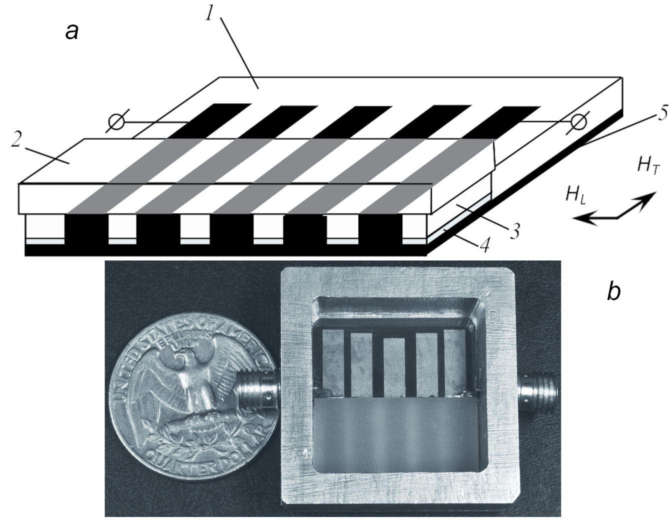

Fig. 4. (a) Structure and (b) photo of the PS. 1: microstrip substrate with high dielectric permittivity ($\varepsilon = 80$). 2: inverted stripline alumina substrate. 3: glass substrate of a thin film. 4: thin magnetic film. 5: grounded plate.

IV. Resonant Magnetically Tunable Phase Shifters

Two types of resonant tunable phase shifter with various magnetic materials have been designed and fabricated. Both of them have the same structure of five-resonator quarter-wavelength bandpass filter with electromagnetic coupling between the resonators.

In designing the device, we used an approach described in [15] and [16]. It bases on the use of physical rules and does not use any prototype low-pass filters, equivalent circuits, coupling coefficients, and so on. With the help of the approach and 3-D simulation (CST Microwave Studio) a parametric synthesis of the device was carried out which provided us with sizes of resonators and gaps between them. Resonator's strip conductors were fulfilled using photolithography and chemical etching.

Structure and top view of the device without cover are shown in Fig. 4. It can be seen that the devices comprises two parts: 1) dielectric substrate having high dielectric constant ($\varepsilon = 80$, thickness $h = 0.5$ mm) containing five parallel strip conductors on its top and 2) inverted alumina substrate ($\varepsilon = 9.8$, $h = 0.5$ mm) suspended at 0.5 mm above a grounded plate, with 5 parallel strip conductors on its bottom face. These conductors are connected by their one ends with strip conductors on the first substrate and their other ends are short-circuited. So, these five strip conductors form five quarter-wavelength resonators. In the 0.5 mm gap between the inverted substrate and the grounded plate a magnetic material is placed: in this part of the resonator the maximal magnitude of MW magnetic field is located. Strip conductors of the inner resonators are shortened for the purpose of trimming. Both substrates in the device have practically the same size and the housing inner size of both PS is the same: 22 mm × 23 mm. Magnetic fields (H_L and H_T in Fig. 4) were created by two

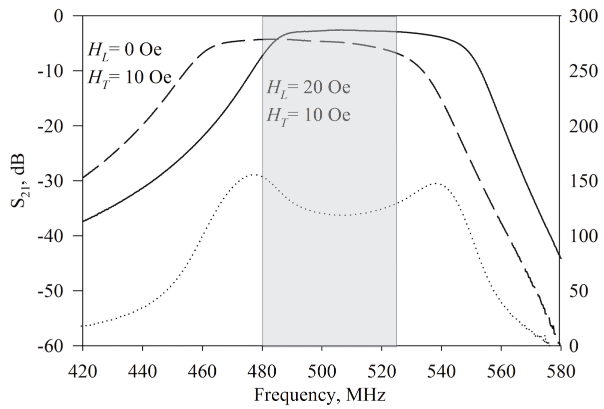

Fig. 5. Frequency responses of thin film phase shifter for two phase states corresponding to the field combination $H_T = 10$ Oe, $H_L = 20$ Oe (solid line), and $H_T = 10$ Oe, $H_L = 0$ Oe (dashed line), and frequency dependence of tunable phase shift corresponding to such field changing (dotted line).

orthogonal pairs of Helmholtz coils. Index L indicates the constant field directed along the MW magnetic field generated by the resonators and T concerns to the orthogonal field. In fact, H_L serves to eliminate domain structure in the thin magnetic film or YIG ferrite, and by H_T their magnetic state (magnetic permeability) is set.

A. Thin Film-Based Phase Shifter

The thin film resonant phase shifter has the next conductors' pattern parameters: the total lengths of the strip conductors forming external and internal resonators were 19 and 18.5 mm, respectively, and the central one was 18.3 mm; the gaps between the resonators were 0.9 mm between the external and internal resonators, and 1.5 mm between the internal and central resonators. All conductors had a width of 3 mm.

The fractional bandwidth of the device (as a filter) was found to be $\Delta f/f_0 \approx 0.12$ (i.e., 12%), so the loaded Q-factor is estimated as 8.3. The film had parallel orientation of its easy axis relative to the microwave magnetic fields generated by the resonators.

The transmission coefficient and tunable phase shift were measured for different magnitudes and directions of the applied external magnetic field (H_L and H_T) in order to determine that magnetic field algorithm, which is optimal from the point of view of the best figure of merit. It appeared the best result is achieved when $H_T = 10$ Oe, and H_L changes from 0 to 20 Oe. In Fig. 5 the measured frequency responses are presented for two states of PS (solid and dashed line) that correspond to the mentioned values of the fields. The operational bandwidth that is formed by overlapping parts of the transmission bands is indicated by gray color in the figure, and its relative value is 10%. The tunable phase shift corresponding to the field change is presented by dots. It can be seen from the figure that its value is $\Delta\varphi \approx 120°$ at the center of the operational band, that gives figure of merit of ∼40°/dB. We can also see from the figure that the frequency shift is 17 MHz, which corresponds to $\delta \approx 0.016$. So the estimated value of the shift obtained in accordance with (1) is about 140°. This result is in good agreement with the experimental one.

By further changing the external field, we can achieve phase shift up to 180 or even more, but this will reduce the operational bandwidth and, more importantly, will reduce the figure of merit as the transmission loss increases dramatically in this case.

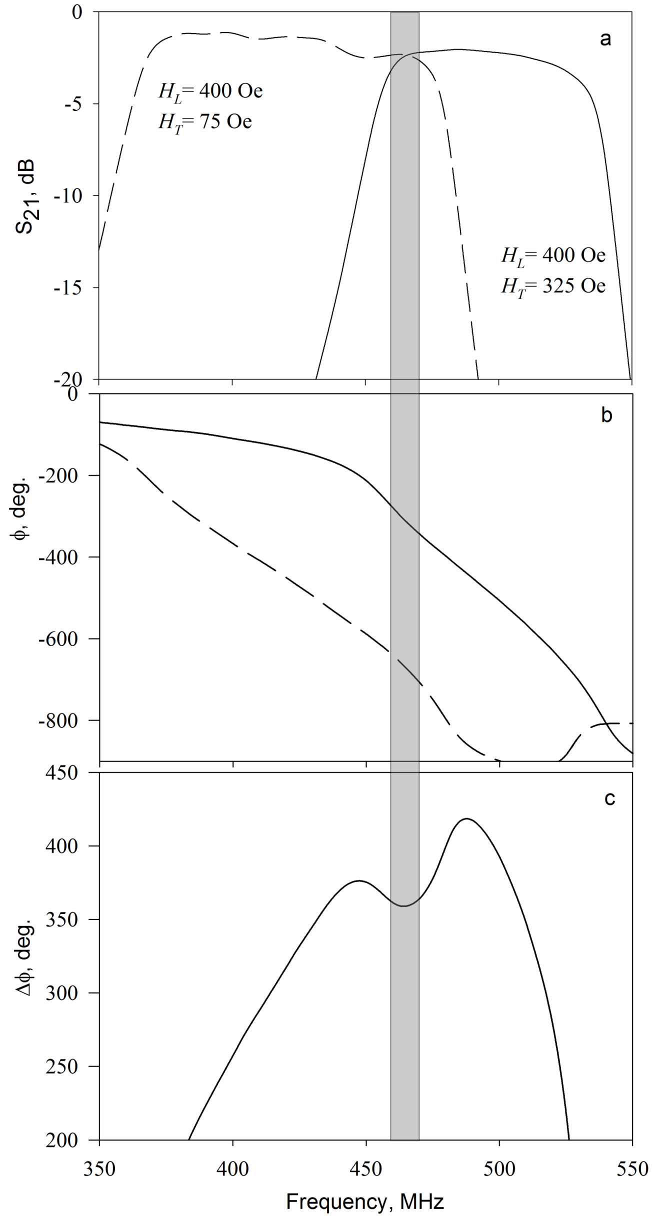

Fig. 6. (a) Frequency responses of the ferrite phase shifter for two field combinations: $H_T = 75$ Oe, $H_L = 400$ Oe (solid line) and $H_T = 325$ Oe, $H_L = 400$ Oe (dashed line). (b) Phase responses for these states. (c) Frequency dependence of the tunable phase shift corresponding to such field change. Gray area: operational band of the device.

B. Ferrite-Based Phase Shifter

In the ferrite resonant phase shifter, the lengths of the external and internal resonators were 19.5 and 19.3 mm, respectively, and the central one was 19.1 mm. The resonators have the same width as that of the previous structure. The gaps between the conductors were 0.3 (external and internal resonators) and 0.6 mm (internal and central resonators). As a bandpass filter, this construction had fractional bandwidth of $\Delta f/f_0 \approx 0.18$ (18%) and this value corresponds to the loaded $Q = 5.6$. The best results on the figure of merit were obtained by applying the constant magnetic field $H_L = 400$ Oe and

TABLE I
COMPARISON OF MAGNETIC PHASE SHIFTERS

Ref.	Phase shift (°)	Insertion loss (dB)	Figure of merit (°/dB)	Field (Oe)	Perfomance $\Delta\varphi/(\Delta S_{21}\Delta H)$ (°/(dB*Oe))
[17]	60	1.5	40	3250	~0.007
[18]	100	2	50	100	
[19]	62-68/cm	10	6.2-6.8	100	~0.062
[20]	172.5	4.5	38	3450	~0.12
[21]	100	2.5	40	70	
[5]	307	4.25	72	100	
[22]	261	21	12.4	1185	13.1
[22]	252	21	12	1245	~26.7
This work	120	3	40	20	~3.1
This work	360	2.4	150	400	~3.1

tuning orthogonal field H_T. The magnitude of H_T in this case varied from 75 to 325 Oe.

In Fig. 6(a), the frequency dependences of transmission loss corresponding to the two limiting values of the tuning field are presented. The relative width of the operating band, in this case indicated by gray color, was ~5%. The average value of the loss inserted by the phase shifter was 2.4 dB. Fig. 6(b) presents the measured phase responses of the device corresponding to the mentioned magnitudes of the fields H_L and H_T. The resultant frequency dependence of the tunable phase shift is presented in Fig. 6(c). Thus, the change in field H_T from 75 to 325 Oe with constant $H_L = 400$ Oe yields phase change around 360°. So the measured figure of merit for the device was found to be ~150°/dB.

There are two possible reasons for why YIG ferrite-based phase shifter has a superior performance over NiFe-based PS. First, PS with YIG has a larger filling factor than that of with NiFe. Second, its losses are less because YIG has less tangent of magnetic loss compared with NiFe film and is dielectric, so in contrast to the film, it has no Joule's loss.

From the results presented in Fig. 6, one can obtain 81 MHz of frequency shift and $\delta \approx 0.09$. This gives us 320° phase shift estimated in accordance with (1). This figure agrees well enough with the experimental one too. The discrepancies in both the cases may be attributable to the simplifications made in derivation of (1).

A simulation of the phase shifter was carried out in CST Microwave Studio, which has shown that for the ferrite in the experiment, the change of μ was only from 1.0 to 1.6.

V. CONCLUSION

Two magnetically tunable phase shifters were presented based on resonant principle. Two types of magnetic materials were used as an active media in the phase shifters: 1) five-layer thin magnetic film NiFe and 2) YIG ferrite. The thin film phase shifter with relative operational bandwidth 10% has tunable phase shift $\Delta\varphi \approx 120°$ that corresponds to the figure of merit of ~40°/dB. This value is not inferior to the current values achieved recently (Table I). The main advantage of the proposed structure is low value of tuning magnetic field (only 20 Oe for $\Delta\varphi = 120°$), which gives an opportunity to use such construction as a part of chip integrated circuit.

On a ferrite phase shifter with relative operational bandwidth 5%, the 360° phase shift was achieved that corresponds to the figure of merit of 150°/dB. This value significantly exceeds the levels currently achieved with planar construction, not only with magnetic tuning but also for the majority of planar phase shifters with other types of tuning methods and active media (liquid crystals, ferroelectrics, semiconductor varactors, and MEMS).

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