Tunable negative refractive index metamaterial phase shifter

P. He, P.V. Parimi, Y. He, V.G. Harris and C. Vittoria

A tunable compact phase shifter utilising negative refractive index metamaterial is demonstrated. The negative index metamaterial is composed of a periodic copper wire pattern sandwiched between two slabs of high quality yttrium iron garnet films. Near ferrimagnetic resonance, a phase shift tuning of 160°/kOe is achieved at 24 GHz. The insertion loss varies from 4 to 7 dB for a 1 cm-long composite.

Introduction: Phase shifters are critical elements in several electronically tuned microwave systems in defence, space and commercial communications applications. The excessive cost and weight of phase shifters has limited deployment of electronically scanned antennas in some aerospace applications. While digital diode based phase shifters may withstand high power of the order of a few tens of watts, by virtue of their nature, the accuracy in phase shift is limited. Hence there is significant demand in the microwave industry for affordable, light weight, high power phase shifters. Microwave ferrite phase shifters can generally handle higher power than competing technologies, e.g. commercial ferrite phase shifters can operate at an average power of up to 100 W and peak power 2000 W. In ferrite phase shifters a change in permeability by the application of magnetic field causes a change in the phase velocity of the microwave signal travelling through the phase shifter. To be useful in microwave systems, a phase shifter should exhibit low insertion loss, minimal variation in the insertion loss with phase shift, and low return loss. Recent advances in metamaterials possessing negative index of refraction (NIM) and strong dispersion characteristics with high value of $dn/d\omega$ ($\theta = n\omega\Delta L/c$) has opened the doors for novel microwave technologies, where n is the index of refraction, θ is the phase change of the signal through the material, ΔL is the length of the material and c is the velocity of light. A significant recent development in the field of NIM is the fabrication of tunable negative index materials [1]. The tunability and low loss observed in the NIM make them ideal materials for designing tunable, compact and lightweight phase shifters.

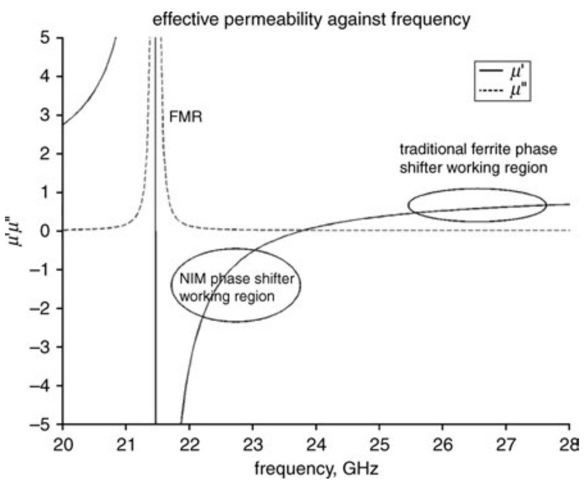

Fig. 1 *Schematic diagram of NIM composite mounted in K-band waveguide*
The complex permeability is defined as $\mu = \mu' - j\mu''$

Traditional ferrite phase shifters operate at frequencies away from the FMR in order to avoid absorption losses near the FMR frequency. As a result, the real part of the complex permeability, μ', is necessarily small. Reference [1] reported experimental and theoretical investigations of field tunable negative refractive index metamaterial (NIM) using yttrium iron garnet (YIG) and an array of copper wires in a K-band waveguide and demonstrated it as being a key feature of magnetic field tunability of the NIM in the microwave frequency region. A transmission passband was realised in the negative refractive index region that could be tuned by the external magnetic field. The permeability of the NIM was simultaneously tuned along with refractive index. The change in permeability or refractive index leads to a change in the phase velocity of the signal and therefore the phase of the transmission coefficient. The schematic design is shown in Fig. 2.

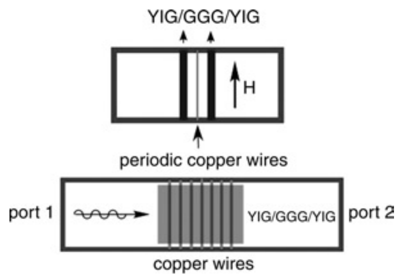

Fig. 2 *Calculated complex permeability of high quality single crystal YIG films showing different working frequency regions for traditional and NIM phase shifters*

NIM materials possess many fascinating electromagnetic properties such as backward wave propagation and amplification of evanescent waves which allow for a super lens with subwavelength resolution imaging, leaky wave antennas, and miniature delays lines. Notable NIMs are resonant metamaterials [2], photonic crystals [3], and planar periodic arrays of passive lumped circuit elements. However, these NIMs are not tunable at all. The advantage of using a ferrite NIM material for phase shifter application is that it allows use of a ferrite in the negative μ' region near the FMR when μ' is relatively high and still maintains low losses [4]. Near the FMR frequency, the magnitude of μ' is larger than that at frequencies away from it. Assuming the loss factor to be about the same for the NIM and the conventional ferrite phase shifter, we would expect a much improved figure of merit using the NIM composite, since the phase shifts would be significantly higher owing to higher differential μ' as illustrated in Fig. 1.

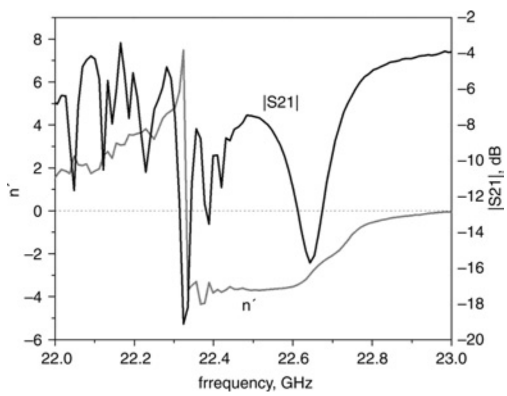

Fig. 3 *Real part of refractive index calculated from phase change difference of transmitted wave of two samples with difference lengths (left scale) and experimentally measured amplitude of S21 for NIM inserted in K-band waveguide (right scale)*

Tunable NIM: In our field tunable NIM, the effect of the YIG films was to provide a tunable negative permeability over a continuous range of frequencies on the high frequency side of the ferrimagnetic resonance. Complementary negative permittivity, ε', is achieved using a single periodic array of copper thin film wires deposited on Kapton^{TM} substrate. Fig. 2 shows schematic diagrams of the two cross-sections of this tunable NIM in a K-band waveguide. The composite structure consisted of copper thin film wires with 25 × 100 μm cross-section spaced 1 mm apart and a multilayered YIG film with a total thickness of 400 μm. The air gap and the Kapton^{TM} substrate played a role in decoupling the interaction between the YIG films and the wires [1, 4]. YIG films were deposited by liquid phase epitaxy on both sides of a gadolinium gallium garnet (GGG) substrate. The thickness of the GGG substrate was 500 μm. The lengths of the two samples used on the direction of propagation were 8 and 4 mm. The condition for the FMR was obtained by applying the external magnetic field of 6.5 kOe, H, along the wires. The sample was mounted in the K-band rectangular waveguide and transmission measurements were carried out using an HP 8510 network analyser. In experiments, two narrow slots were cut on the top and bottom of the waveguide to mount the copper wires. As shown in Fig. 3, a transmission peak centred at 22.5 GHz was observed in the transmission coefficient |S21|. The dip near 22.4 GHz corresponds to the FMR. Another dip near 22.6 GHz is due to the effect of antiresonance. Note that near the FMR, the interaction between the wires and the YIG slabs is very strong, causing modulations to the |S21|.

To determine the real part of the index of refraction n' unambiguously [5], we carefully measured the S-parameters of the two samples having different lengths. To measure the phase changes of the S21 of the two samples, the reference planes of the scattering matrix were set to the two ends of the sample by de-embedding. By subtracting them, we obtained the absolute phase change, $\Delta\varphi$, of S21 after propagating through the 4 mm NIM sample. n' is calculated as described in the equations below. In the equations, ΔL is the length difference of the two samples, k_0 the propagation constant of free space and a the transverse dimension of the K-band waveguide. In the square root, the second term is very small compared with the first one at high frequencies.

$$\Delta\varphi = \beta \cdot \Delta L = \Delta L \cdot \mathrm{Re}[\sqrt{(n' - jn'')^2 k_0^2 - (\pi/a)^2}] \simeq \Delta L \cdot n' k_0 \quad (1)$$

$$n' \simeq \Delta\varphi / \Delta L \cdot k_0 \quad (2)$$

We found that $\Delta\varphi$ had a discontinuity at the FMR frequency and so is the index of refraction. In Fig. 3, a negative refractive index region of 0.5 GHz width is determined from the measurements. Although theoretically YIG has a negative μ' region with a band width of up to 2.5 GHz, the small negative refractive index region is due to the small volume factor of the YIG slabs. Increasing the volume of the YIG will increase absorption. Therefore there is a trade-off between wide band width for the negative index region and low loss. In addition, the dielectric permittivity of the YIG slabs reduces the effective negative permittivity obtained from the plasmonic copper wires.

Phase shift performance: We studied the phase shift of a 1 cm-long sample as well as the insertion loss performance of the 8 mm-long sample as shown in Fig. 4. At 24 GHz, when the applied magnetic field was varied from 6.0 to 7.0 kOe, the phase varied 160° with the insertion loss varying from 4.3 to 6.3 dB. At the lower field side, the phase change was smaller. The phase shifter was operated at the frequency above the ferrimagnetic antiresonance with a positive permeability with the material having a positive refractive index. At higher fields, the phase was more sensitive to field tuning, which corresponded to the negative refractive index region as illustrated in Fig. 1. Over all, the insertion loss had a variation of 2 dB, as a result of variation in wave impedance owing to variation of the permeability.

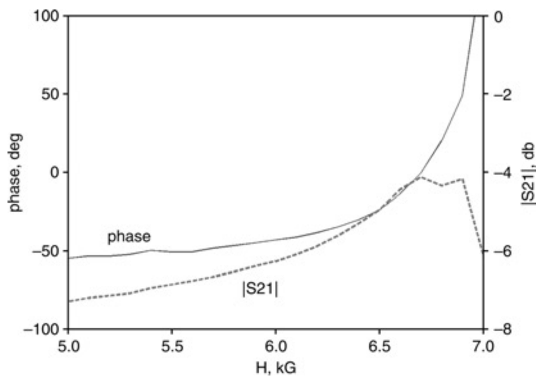

Fig. 4 *Measured insertion phase shift and insertion loss (|S21|) against applied external magnetic field at 24 GHz*

Conclusion: We have demonstrated a waveguide field tunable phase shifter using an NIM composite. It is the first application of its kind. Continuous and rapid phase tunability of 160°/kOe was realised with an insertion loss of 4 to 7 dB at 24 GHz. The phase change in the negative refractive index region is more sensitive to field tuning compared to the phase change of the positive refractive index region over the ferrimagnetic antiresonance. This introduces a new method of fabricating effective high power and compact phase shifters.

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