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High Temperature Superconducting Ferrite Phase Shifter with New Latching Structure

Kenneth S. K. Yeo and Michael J. Lancaster

***Abstract*—Superconductor ferrite phase shifters are attractive for phased array radar systems. The huge reduction in size and losses mean that smaller systems are possible. This paper reports a new latching structure for a superconducting ferrite phase shifter which is compact in size and has low losses. The total size of the phase shifter is 6.0 cm x 3.0 cm x 2.5 cm including housing. It should be pointed out that two phase shifters can be accommodated in this size. The minimum insertion loss of the designed phase shifter was measured at 0.8 dB. The phase shifter is fabricated using a Yttrium Barium Copper Oxide (YBCO) microstrip meander-line on a one centimeter square low loss sapphire substrate. We press contacted a magnetized ferrite substrate, with a silver ground plane, onto the fabricated YBCO meander-line to obtain non-reciprocal phase shifting. To magnetize the ferrite substrate without causing magnetic field penetration into the high temperature superconductor (HTS), we propose a new latching structure comprising a single ferrite layer with magnetizing coils. This new structure will confine the magnetic field within the ferrite substrate by providing a closed magnetic path. This is achieved by making a large hole at center of the ferrite substrate.**

***Index Terms*—Superconductor Device, Ferrite phase shifter.**

I. INTRODUCTION

Low loss microwave phase shifters are important devices in phase array radar and communication systems.

Conventionally, low loss ferrite phase shifters were designed using ferrite loaded waveguide, which is large and bulky. Planar printed circuit technology, e.g. microstrip structure, is very attractive in replacing the waveguide technology. However, one has to sacrifice the performance for the size reduction because of the conductor loss which inhibited in normal microstrip structures. Since the discovery of high temperature superconductor (HTS) in 1986, conductor loss is no longer the main loss contributor in microstrip structure. By replacing the normal metalisation in microstrip with HTS material, huge improvement in the insertion loss can be achieved.

Replacing the normal conductor in microstrip with HTS material seems very promising in reducing the conductor loss. However, there are some complications when HTS materials are incorporated in ferrite microstrip devices. This is mainly due to the biasing magnetic field that is used to operate the ferrite devices. HTS materials have a very special property that is the quenching of the superconducting phenomena when penetrated by a high magnetic field. Therefore, the structure of the magnetizing circuit is crucial to ensure that there is no (or minimum) magnetic field penetration into the superconducting films. Strong magnetic field penetration into superconducting film will degrade the performance of the superconductor and will result in high loss or even destroy the properties of the superconductor all together.

Here, we propose a new latching structure which will provide maximum flux confinement and minimum magnetic field penetration. This new structure will only use a single ferrite layer substrate. Therefore, this structure is easier to construct compared to two piece ferrite structures [1-4]. In this design, low loss and low saturation magnetization ferrite material is used as the HTS microstrip substrate. Because HTS thin film cannot be grown on polycrystalline ferrite, a substitute substrate is used to grow the HTS thin film. Here, the HTS thin film is grown and fabricated on a low loss sapphire substrate and then inverted onto the ferrite substrate.

II. PRINCIPLE OF OPERATION

This section gives a brief introduction of the meander-line ferrite phase shifter [5, 6]. A non-reciprocal phase shifter is more desirable compared to a reciprocal phase shifter because the former produces larger phase shift. Non-reciprocal phase shift can be achieved by using a microstrip with meander-line structure as shown in Fig. 1. The meander-line is used to produce circular polarization at the center of the meander element (i.e. at point A). Circular polarization is important because it is needed to achieve non-reciprocal operation.

The meander elements length, L, are designed to be quarter wavelength, i.e.

$$L = \lambda / 4 \tag{1}$$

where λ is the wavelength at the operating frequency. Because of (1), the current, I_2, flowing in line 2 is 90° delayed in time relative to the current, I_1, flowing in line 1 as shown in Fig. 1. The magnetic fields, H_1 and H_2, which are produced by the current in line 1 and line 2, respectively, are spatially orthogonal at point A. If the spacing, P, of the meander element is smaller than the height of the ferrite substrate, the resultant rf magnetic field is right hand circularly polarized relative to the direction into the diagram.

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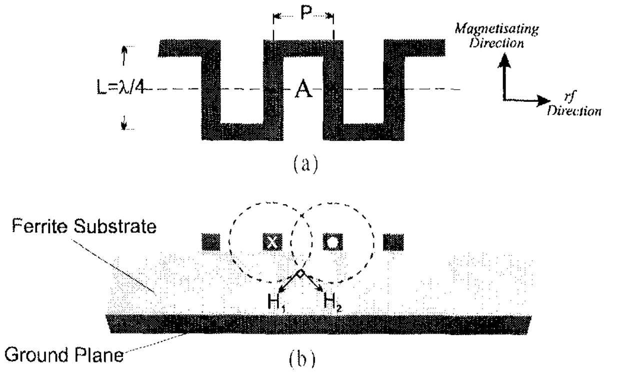


Fig. 1: Meander line structure (a) top view showing the microstrip meander (b) side view showing the conducting ground plane, ferrite substrate and a section through the meander with an indication of the magnetic field directions.

When a magnetic field is biased longitudinally along the element direction as shown in Fig. 1, a strong interaction occurs between this magnetizing field and the *r.f.* circularly polarized field. As a result, the propagation constant β is changed. Therefore, the insertion phase of the device is altered. When the device is latched with a magnetic field of opposite direction, the latched magnetic field will sense an opposite direction of circular polarized wave, e.g. left hand circular polarized. Therefore, the device is in non-reciprocal operation.

For a normal conductor ferrite phase shifter, the biasing can be achieved by coiling wire around the meander-line microstrip. Because the normal conductor does not deteriorate with magnetic field penetration, this simple biasing method will not cause any severe disadvantage. However, when a superconductor is used to replace the normal conductor meander-line, the biasing circuit becomes an important factor in the design. The following section will address this design factor.

III. NEW LATCHING CIRCUIT

A magnetic circuit is used to produce the external biasing magnetic field. Special consideration is needed when designing this magnetic circuit. It is of great importance that the magnetic field produced by this circuit will not penetrate the superconducting meander-line.

To achieve maximum flux confinement, we propose a planar structure as shown in Fig. 2. A closed magnetic path of the biased magnetic field will ensure maximum flux confinement. To achieve this closed path, we made a large hole at the center of the ferrite substrate. The current loops are placed relatively far from the HTS meander-line. This is to ensure that the flux leakage from the current loop will not penetrate the fabricated HTS thin film.

Fig. 2 shows only a single phase shifter. With the same substrate, a second phase shifter can be designed and placed on the right of the ferrite substrate as shown in Fig. 3. This will reduce the total size per phase shifter. To achieve a different phase shift for the second phase shifter, a different number of meander-lines can be used, e.g. the first phase shifter is fabricated with 8 meander sections and the second phase shifter with 6 meander sections. Therefore, the two phase shifters can have different phase shift with just a single biasing control. Here, we will only present the experimental results of a single phase shifter.

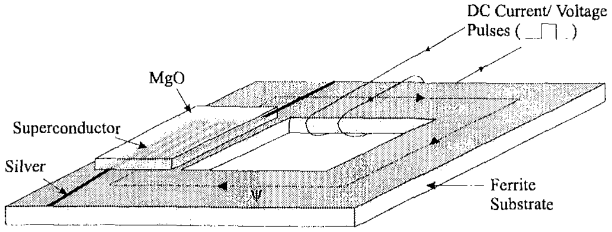


Fig. 2: The new HTS ferrite phase shifter design layout.

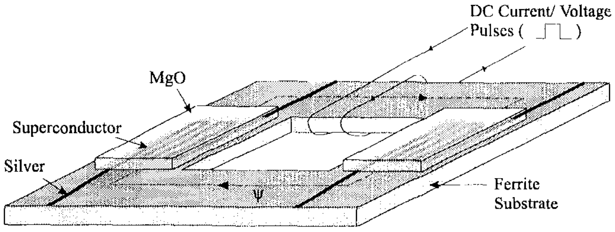


Fig. 3: Two phase shifters on a single substrate

IV. EXPERIMENT RESULTS

Fig. 4 shows the assembled HTS ferrite phase shifter with the gold plated lid removed. Yttrium Aluminum Iron Garnet (YAIG-Y9A) is used as the ferrite substrate in this design. YAIG-Y9A has a saturation magnetization, M_s, of 79.6 kA/m (1000 G) and dielectric constant of 14.4 at room temperature. The meander-line is fabricated using YBCO on 1.0 cm x 1.0 cm sapphire substrate. The fabricated HTS circuit is then press contacted to the ferrite substrate using a spring. Silver epoxy is used to make contact between the fabricated YBCO meander line to the fabricated silver microstrip feed lines on the ferrite substrate. Sliding contacts with silver epoxy are used to connect the silver microstrip line to the center pin of the input and output SMA connectors. The ferrite is fitted into a gold plated titanium box for measurement. Titanium material is preferred over brass for the housing because the former has a lower thermal expansion coefficient. This is to ensure that the ferrite substrate will not break with a large temperature variation, e.g. cooled from room temperature to 60K. A silver ground plane is used in this design. An HTS ground plane can be incorporated in this design.

The assembled HTS phase shifter is cooled down to 60 K using a closed cycle cryostat for measurement. The measurement is carried out using a HP8720A network analyzer. The network analyzer is calibrated at cryogenic temperature using a short 50Ω transmission line. Fig. 5 shows the measured responses of the phase shifter. A very promising insertion loss has been achieved. A differential phase shift of 55° has been achieved with ±1.0A current biasing. This is not the maximum differential phase shift that can be achieved. With 1.0A biasing current, the magnetization of the ferrite is just slightly above the remnant magnetization. By increasing the number of current loops or increasing the biasing current, a higher differential phase shifting can be achieved. A much higher phase shift can be achieved, if the ferrite can be magnetized to its saturation. Another method to produce the magnetic field is to use voltage pulse with a fixed time duration[3].

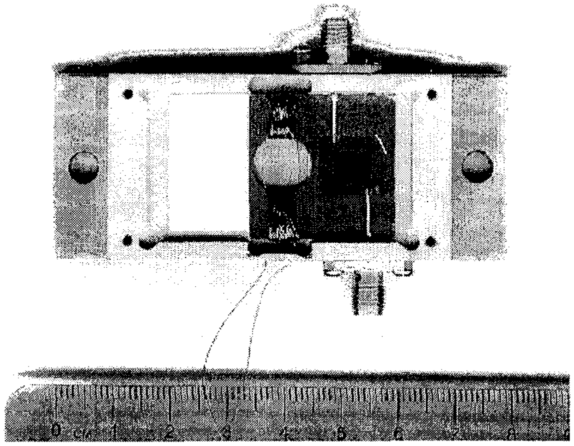
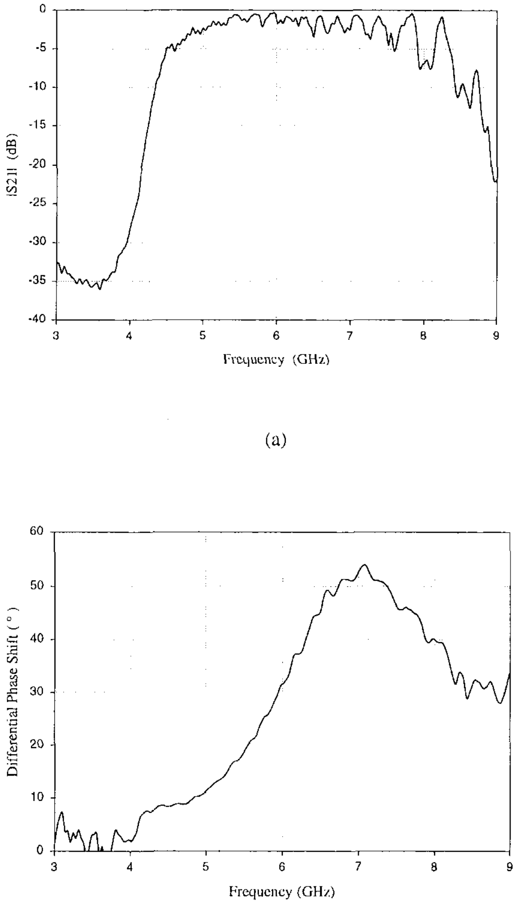


Fig. 4: Top view of the assembled phase shifter with the lid removed.

The experimental results show that the average insertion loss is about 1.5 dB at the operating frequency. The minimum insertion loss measured is about 0.8dB. The major part of the insertion loss can be attributed to the silver feed-lines used to connect the YBCO meander line to the input/output connectors. The high losses at higher frequency, which is approximately twice the operating frequency, are due to the bandstop nature of the meander-line. At lower frequency (below 4.5 GHz), the high losses are mainly contributed by the ferrimagnetic resonance loss of the partially magnetized ferrite substrate [7]. Theoretically, the ferrimagnetic resonance frequency, f_s, is given by

$$f_s = \gamma 4\pi M_s \tag{2}$$

where γ is the gyromagnetic ratio and M_s is the saturation magnetization of the ferrite substrate at room temperature. Based on (2), the calculated f_s is 2.8 GHz. However, this value does not tally with the experimental result. This is mainly due to the temperature dependent of M_s parameter. When the temperature is reduced to 60 K, M_s is increased by approximately twice its value at room temperature.



(a)

(b)

Fig. 5: Measured response of the HTS phase shifter at 60 K, (a) insertion loss (b) differential phase shift with 1.0A of biasing.

V. CONCLUSION

A new latching structure for HTS ferrite phase shifter has been presented. Experimental results are also shown in support of this newly proposed structure. A brief introduction of the meander-line microstrip phase shifter has also been discussed. Designing the second phase shifter onto the same substrate is a good way to reduce the total size per phase shifter.

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