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STUDY OF X-BAND PHASE SHIFTER USING FERRITE MATERIAL *

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Abstract

Ferrite has the feature of the permeability depended on the external static magnetic field, thus could be used to shift the phase of the propagating radio frequency (RF) signal. In this paper, we introduce a novel design of ferrite-based RF phase shifter. The design changes the resonant frequency of a ferrite-filled pill-box cavity to implement the phase changing. This design has a lower local RF field and a larger sensitivity on the phase changing than those of waveguide phase shifter, which may bring advantages such as capacity of transmitting high power, fast changing speed and lower insertion loss. Theory and simulation results are presented in this paper.

INTRODUCTION

Phase shifters are critical components in many RF and microwave systems such as antennas, radars and mobile communications. In the accelerator field, controlling the phase of input or output RF power by a phase shifter has also been developed for years. Mechanical phase shifters were firstly invented and put into application [1]. Due to the limitation of the motor speed, normally a few seconds are needed to do the shift, which is not satisfied in some fast-action applications.

Another kind of phase shifters insert ferrite-based materials to change the phase. The ferrite material has the feature of the permeability depended on the external static magnetic field. So the phase could be changed by this external field and the response time could be less than milliseconds. Several waveguide phase shifters using ferrite had been developed and tested [2-3]. The fast response time, high power capacity and the large phase-shifting range are considered in priority, and the low RF insertion loss is required. For this reason, a low loss yttrium iron garnet (YIG) ferrite material was commonly used and had been proved to be effective. However, the phase-shifting range is achieved at the expense of large-current change of electric magnets.

In Tsinghua University, an X-band SLED-I type pulse compressor is being developed and tested. This pulse compressor consists of a resonant cavity and an RF polarizer. An over-coupled resonant cavity has a feature of that the phase of its reflected wave is sensitive on the difference between the resonant frequency and the one of the input signal. This phenomenon enlightens us that inserting ferrite materials in a cavity to tune the frequency and shift the RF phase. And this design is believed to have larger phase shift and phase change rate.

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BASIC THEORY

Ferrites

Ferrites are polycrystalline magnetic oxides that can be described by the general chemical formula $XO.Fe_2O_3$, where X is a divalent ion such as CO^{2+} or Mn^{2+}. The RF power can pass through these oxides easily as they have a much lower conductivity than metals [4]. Ferrites are classified into permanent magnetic ferrite, soft magnetic ferrite and gyromagnetic ferrite with different characteristics. Gyromagnetic ferrites, also called microwave ferrites are commonly used in phase shifters and exhibit anisotropy of magnetic permeability. The relationship between the magnetic flux density B and the magnetic field intensity H can be expressed as:

$$B = (\mu)H$$

$$(\mu) = \begin{pmatrix} \mu_{11} & \mu_{12} & \mu_{13} \\ \mu_{21} & \mu_{22} & \mu_{23} \\ \mu_{31} & \mu_{32} & \mu_{33} \end{pmatrix} \quad (1)$$

$$\mu_{ij} = \begin{cases} \mu_0(1+\chi_{ij}), & i = j \\ \mu_0\chi_{ij}, & i \neq j \end{cases}$$

where (μ) is the tensor permeability.

Resonant Cavity

A resonant cavity coupled with a transmission system can be regarded as an equivalent LCR circuit connected with an ideal transformer, as shown in Fig. 1 [5].

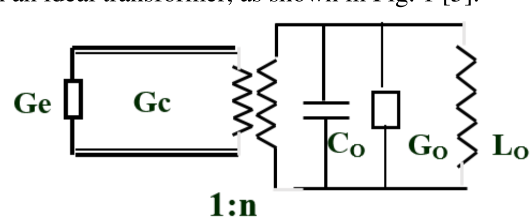

Figure 1: The equivalent circuit of a resonant cavity coupled with a transmission system.

The admittance of the resonant cavity seen by the transmission system is expressed as:

$$Y(\omega) = G_0 + \frac{1}{j\omega L_0} + j\omega C_0$$

$$= G_0 + j\omega_0 C_0\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) \quad (2)$$

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where $\omega_0^2 = \frac{1}{L_0 C_0}$.

At the resonance, the unloaded quality factor Q_0 of this circuit is

$$Q_0 = \omega_0 C_0 / G_0 \quad (3)$$

from which

$$Y(\omega) = G_0 + jG_0 Q_0 (\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}) \quad (4)$$

And the loaded quality factor Q_L is

$$\begin{aligned} Q_L &= \omega_0 C_0 / (G_e + G_0) \\ &= 1/\left(\frac{G_e}{\omega_0 C_0} + \frac{G_0}{\omega_0 C_0}\right) \\ &= Q_0/(1+\beta) \end{aligned} \quad (5)$$

where $\beta = G_e/G_0$ is the coupling coefficient.

When the operating frequency deviates from the resonance frequency, the admittance of the shunt-resonant circuit changes rapidly not only in magnitude but also in phase, which relates to the reflection coefficient directly. Same results can be concluded if the resonant frequency deviates from the operating frequency. By inserting ferrite inside the resonant cavity in an appropriate place, we can change the resonant frequency by external static magnetic field excited by a solenoid. However, the rapid phase shift is accomplished at the expense of an increase of the reflected power from the cavity. According to the definitions of quality factors, if the cavity is over-coupled, the power loss outside the cavity is greater than the loss inside. Therefore, by optimizing the coupling coefficient (β), we can find a trade-off solution considering both lower reflected power and the large phase shift rate.

RF DESIGN

RF Polarizer

The RF polarizer transmits the TE_{10} mode from one rectangle port to two TE_{11} cylindrical modes in quadrature in the circular port, as shown in Fig. 2. When the input TE_{10} wave travels to the middle part of the polarizer, which is a large size rectangle waveguide, a TE_{20} mode is excited satisfying the boundary condition. Both two modes excites the TE_{11} mode into the circular waveguide with a phase difference of 90 degrees, which the isolation of two rectangle ports is depended on. The S-parameter matrix can be expressed as [6]:

$$S = \begin{pmatrix} 0 & 0 & \sqrt{2}/2 & -\sqrt{2}i/2 \\ 0 & 0 & -\sqrt{2}i/2 & -\sqrt{2}/2 \\ \sqrt{2}/2 & -\sqrt{2}i/2 & 0 & 0 \\ -\sqrt{2}i/2 & -\sqrt{2}/2 & 0 & 0 \end{pmatrix} \quad (6)$$

where the four ports in order represent port 1, port 2, the first and the second modes in port 3 respectively.

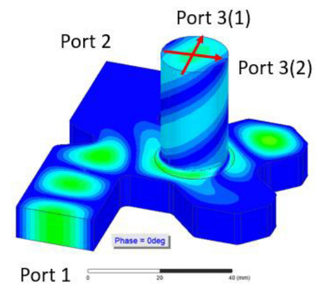

Figure 2: The simulation model of the revised RF polarizer.

The revised RF polarizer removes the bottom circular part. This bottom part was initially designed for enhancing the transmission to the circular waveguide and accessing to a vacuum pump. As a vacuum pump is not specifically needed here in our design, removing its bottom simplifies the mechanical design and fabrication. The revised version shows good RF characteristics in our simulation, as shown in Fig. 3.

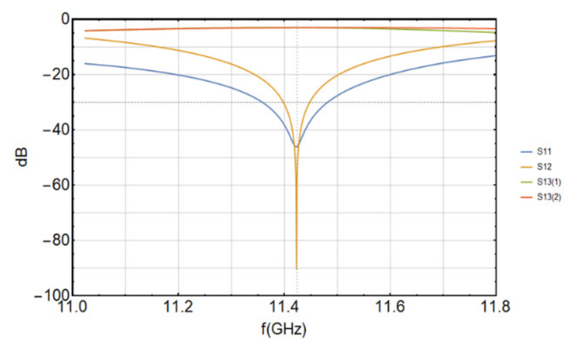

Figure 3: The simulated S-parameters of the revised RF polarizer with the resonant frequency of 11.424 GHz.

Frequency Detuning Simulation

Simulations were carried out to examine this idea. A cylindrical cavity is selected for simplicity. This cavity implements TE_{113} mode at the frequency of 11.36 GHz, with the unloaded quality factor Q_0 of 25,000 and the coupling coefficient (β) of 7. A one-side open waveguide model is also simulated for comparison, as shown in Fig. 4. Two same size materials are placed at the ends of two models respectively.

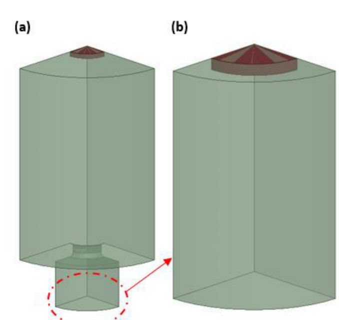

Figure 4: (a) The resonant cavity model; (b) The waveguide model.

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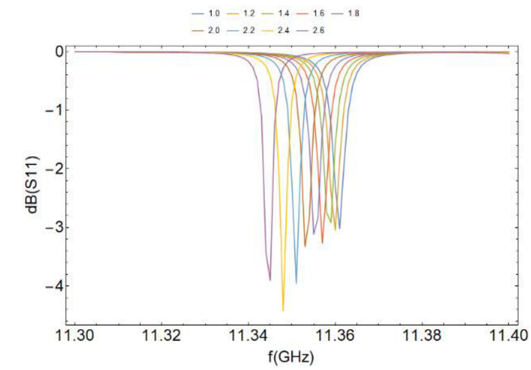

Figure 5: The reflection coefficient curves of the cavity model with different values of the relative permeability.

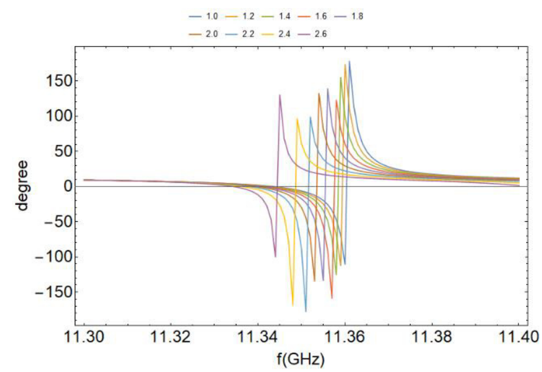

Figure 6: The phase curves of the cavity model with different values of the relative permeability.

We directly change the relative permeability of the inserted from 1 to 2.6 with an interval of 0.2. The reflection coefficient result at the frequency from 11.30 GHz to 11.40 GHz is shown in Fig. 5, and the phase information is shown in Fig. 6. With the value of the relative permeability increased, the resonant frequency of the cavity decreases, together with the reflection coefficient and the phase changed rapidly at the specific frequency. The phase of the waveguide model changes linearly with both the frequency and the relative permeability value and its reflection is at a nearly same level. We assume an operating frequency of 11.36 GHz, and a comparison is shown in Figs. 7 and 8. During the frequency detuning process, the output power of the resonant cavity has a rapid change in phase and magnitude while the same parameters change little for the waveguide output. Optimizations and more realistic conditions will be considered.

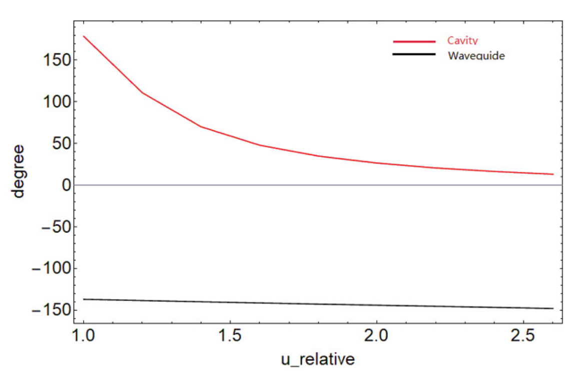

Figure 7: Phases at 11.36 GHz with different μ values.

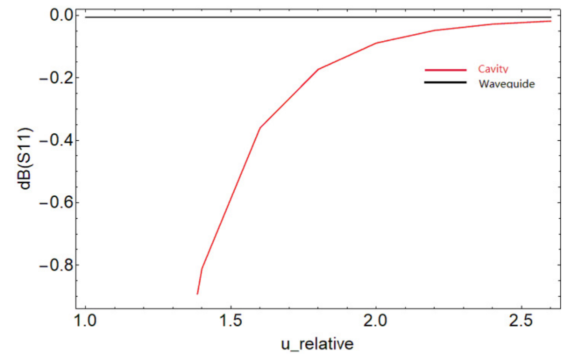

Figure 8: The reflection coefficients at 11.36 GHz with different μ values.

CONCLUSION

Ferrite has the feature of the permeability depended on the external static magnetic field. During the frequency detuning process of a resonant cavity, the reflected power changes rapidly in both phase and amplitude. Ferrite in a resonant cavity rather than in a waveguide has a larger sensitivity on the phase changing at the expense of the amplitude changing of the output power. Optimizations of the coupling coefficient (β) and more realistic conditions will be considered.

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