A Numerical Sensitivity Analysis of a Waveguide Ferrite Phase Shifter

Zahra Habibi[1], Morteza Kazerooni[2], S. H. Mohseni Armaki[3]
1- Department of Electrical Engineering, Malekeashtar University of Technology, Tehran, Iran
Email: zahra_habibi560Yahoo.com
2- Department of Electrical Engineering Malekeashtar University of Technology, Tehran, Iran
Email: mr_kazerooni@Yahoo.com
3- Department of Electrical Engineering Malekeashtar University of Technology, Tehran, Iran
Email: mohseni@ee.iust.ac.ir

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ABSTRACT:
Phase shifters are devices, in which the phase of an electromagnetic wave of a given frequency can be shifted when propagating through a transmission line. In many fields of electronics, it is often necessary to change the phase of signals. RF and microwave phase shifters have many applications in various equipments such as phase discriminators, beam forming networks, power dividers, linearization of power amplifiers, and phase array antennas. Phase shifters are divided into two group diode and ferrite. In this paper a ferrite phase shifter is investigated. Ferrite phase shifters are two-port devices that may be either analog or digital with either reciprocal or nonreciprocal characteristics. In previous works, magnetic flux density-magnetic field intensity curve or B-H curve of a ferrite core is obtained. In this paper, phase shift-current curve or ⌀-I curve of a reciprocal analog ferrite phase shifter is simulated and the effect of various parameters tolerances, such as permeability, permittivity, frequency and length of ferrite rod on the ⌀-I curve is shown.

KEYWORDS: Ferrite phase shifter, Hysteresis curve, Tolerances.

1. INTRODUCTION

A ferrite is a ceramic-like metal–oxid insulator material that its dielectric constant is in the range from 10 to 20. Ferrite materials have a high resistivity and low loss for the electromagnetic waves propagation through the material. They are generally used at the higher microwave frequencies because in this material, loss decreases with increasing microwave frequency [1].

Ferrite phase shifters use of ferrite core for phase-shifting. It is noticeable that the performance of the ferrite phase shifters is dependent on the hysteresis curve of the ferrite material. Ferrite phase shifters are two-port devices that may be either analog or digital with either reciprocal or nonreciprocal characteristics. They have been in use for a long time, especially in combination with waveguide transmission line technology. According to Fig.1 a basic ferrite phase shifter consists of a rod of ferrimagnetic material, centrally positioned inside a waveguide, where a solenoid is wound around the waveguide. If the current changes in the solenoid, the magnetic field is changed and thereby the permeability(μ) of the ferrimagnetic rod and thus the phase of a wave going through the waveguide is changed [1-2].

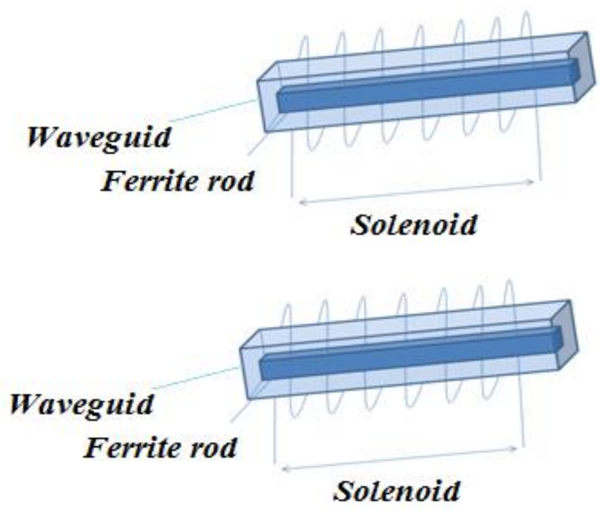


Fig. 1. A basic phase shifter configuration

This paper focuses on the effect of important parameters in phase-shifting and extracts the effect of them on the hysteresis curve of a specified ferrite phase shifter. Thus in Section 2, phase-shifting in ferrite materials; in Section 3, simulation of ⌀-I curve for a ferrite phase shifter and in Section 4, hysteresis curve tolerances extraction for a specified ferrite phase shifter is described.

2. PHASE-SHIFTING IN FERRITE MATERIAL

The phase shift of a signal with frequency f, traversing a distance l is [1]:

$$\varnothing = 2\pi f l \sqrt{\epsilon\mu} \quad (1)$$

Where the μ is permeability and ϵ is permittivity. Usually velocity of propagation of electromagnetic waves is taken to be the velocity of light $c = \frac{1}{\sqrt{\varepsilon\mu}}$.

Equation (1) indicates all phase-shifting possibilities [2]:

- phase-shifting by changing frequency (f);
- phase-shifting by changing length (l);
- phase-shifting by changing permittivity (ε);
- phase-shifting by changing permeability (μ).

The ferrite phase shifters use of changing permeability for phase-shifting. The permeability of ferrite can be expressed as a complex scalar quantity. Therefore [3]:

$$\mu = \mu' - j\mu'' \quad (2)$$

The corresponding phase change ⌀ of a wave transiting a line of length L through the ferrite with negligible loss ($\mu'' \approx 0$) [3], is given by [1]:

$$\emptyset \approx 2\pi f L \sqrt{\varepsilon\mu'} \quad (3)$$

According to circular polarization, permeability is considered in the following [3]-[4]:

$$\mu'_{\pm} \approx 1 \mp \frac{\gamma(4\pi M)}{f} \quad (4)$$

Where the precession (labeled +) and (labeled –) are two counter rotating circularly polarized components, one rotating in synchronism and the other in opposition to it; f is the frequency in hertz; in CGS System, γ= 2.8 (GHz/kG[1]) is the gyromagnetic constant and 4πM is the magnetization in G.

A typical ferrite hysteresis loop or B-H curve has been shown in Fig. 2 This curve is the magnetic flux density as a function of the magnetic field intensity for a ferrite material. The applied magnetic field is proportional to the current in the drive wire. When a sufficiently large pulse of current is passed through the drive wire, the magnetization is pushed to saturation region. When the current is then reduced to zero, there exists a remanent magnetization B_r. Similarly, when a large current pulse of opposite polarity is passed through the drive wire, the ferrite becomes saturated with the opposite polarity. Then, when the current is reduced to zero the remanent magnetization of opposite sign is obtained. Thus a ferrite material may take on two values of magnetization $\pm B_r$, obtained by pulsing the drive wire with either a positive or negative current pulse [1].

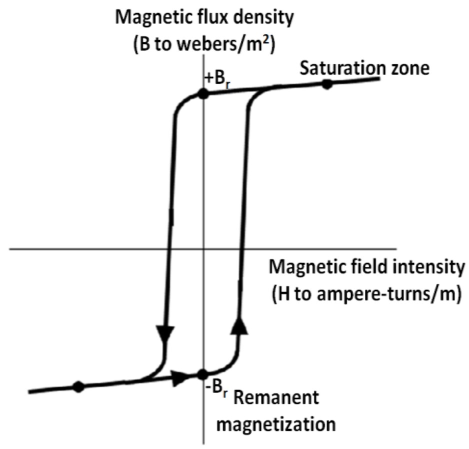


Fig. 2. Typical ferrite hysteresis loop

To access the different phase-shifting, one reference point is necessary, and the set stage should be completed. According to Fig. 3, first point in the set stage is the reference point A, then the amplitude and width of the driving pulse is selected so as to rise to the specified point on hysteresis loop, for example point B in Fig. 3. At the end, the pulse current decays to zero, and Thereby the magnetization falls back to the remanent value. The difference in phase between and reference point determines the differential phase increment [4-5].

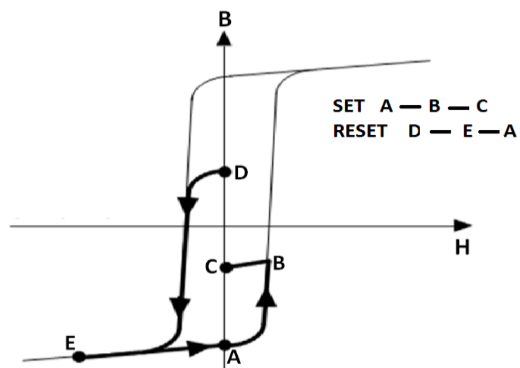


Fig. 3. Ferrite hysteresis loop showing switching cycle

To access the other phase- shifting, the reset stage after the set stage should be completed. According to Fig. 3, at the beginning of the reset stage, the position of curve is in the point such as D. Then a pulse of current beginning of the reset stage, the position of curve is in the point such as D. Then a pulse of current of opposite polarity is passed through the drive wire, consequently the ferrite becomes saturated with opposite polarity (point E in Fig. 3). Then the current is reached to zero, consequently the remanent magnetization of opposite sign that is the same reference point is obtained. Then with a different value of current pulse, a different value of remanent magnetization and a differential phase shift are obtained. It is notable, for a reciprocal ferrite phase shifter only one reference point on hysteresis curve is sufficient. In this manner the ferrite rod is basically an analog device that can provide any phase increment, so it acts as a digital phase shifter if the drive current are digital [1]-[5]-[6].

3. SIMULATION OF FERRITE HYSTERESIS CURVE

In this paper to simulate the hysteresis loop, or B-H curve of a ferrite material, the Basso-Bertotti model [7] is used. In this model the input is magnetic field intensity H, and the output is the magnetic flux density B. Table 1 shows the parameters of the investigated ferrite phase shifter.

Table 1. Parameters of the investigated ferrite phase shifter

Ferrite material	MnZn
Length of ferrite rod	7cm
Ambient temperature	30c
ε = permittivity	17.5
Frequency	9 GHz
number of windings	1500 turns/m

According to Table 1 and (5),(6), Magnetic moment in G - Current in mA curve or 4πM-I curve is extracted from the B-Hcurve [8].

$$B = 4\pi M + \mu_0 H \tag{5}$$

$$\oint \vec{H}.\vec{dl} = NI \tag{6}$$

Where in CGS System, in (5), 4πM is the magnetization to G, μ_0=1(G/Oe)^2 is the permeability of vacuum and H is the magnetic field intensity to Oe) Also in (6), N is the number of windings per meter; L is the length in meter, and is current applied to the coil in ampere [8]. Fig. 4 shows the 4πM-I curve of a ferrite material with a specified phase-shifting.

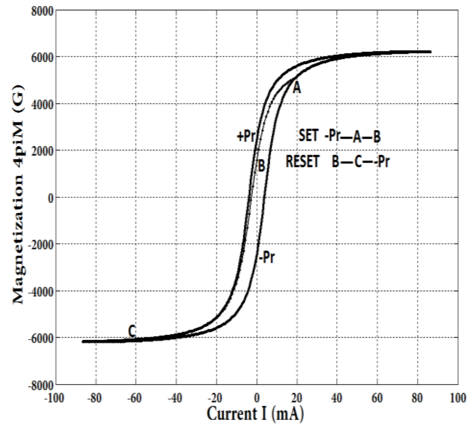


Fig. 4. Simulation of 4πM-Icurve of a ferrite phase shifter showing switching cycle.

According to Fig. 4 to access a specified phase-shifting, the following steps re followed:

1. The hysteresis curve is located in the reference point **-P_r**. Assuming that polarization is circular, the permeability of the ferrite in reference point -P_r is[3]:

$$\mu'_{-P_r} \approx 1 + \frac{\gamma(4\pi M_{-P_r})}{f} \tag{7}$$

2. The amplitude and width of the driving pulse is selected so as to rise to the specified point on hysteresis loop such as point A in Fig. 4.

3. The pulse current decays to zero, and thereby the magnetization falls back to point B in Fig. 4. The permeability of the ferrite in point B is [3]:

$$\mu'_B \approx 1 + \frac{\gamma(4\pi M_B)}{f} \tag{8}$$

4. The difference in phase between B and -P_r determines the differential phase increment. Equation (9) shows the phase increment [3].

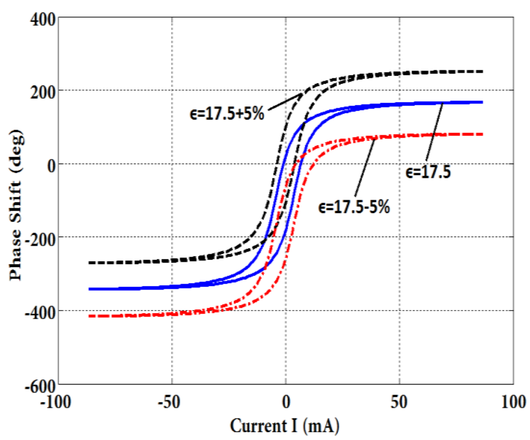
$$\Delta\emptyset = 2\pi f l\sqrt{\varepsilon}\left(\sqrt{\mu'_B} - \sqrt{\mu'_{-Pr}}\right) \tag{9}$$

5. To access the other phase-shifting, a pulse of current of opposite polarity is passed through the drive wire, consequently the ferrite becomes saturated with opposite polarity (point C in Fig. 4). Then the current is reached to zero, consequently the remanent magnetization of opposite sign that is the same reference point -P_r is obtained. Similarly with a different value of current pulse, a different value of remanent magnetization and a differential phase shift are obtained.

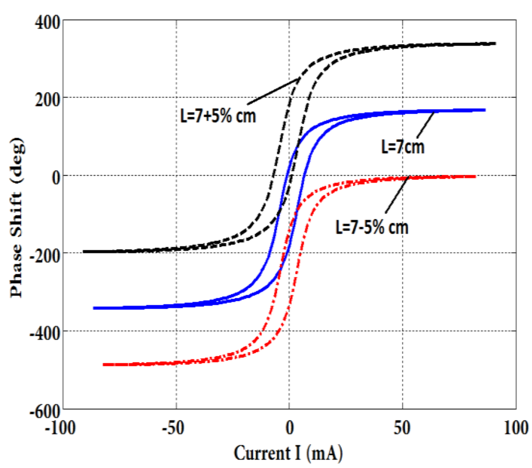
It is noticeable that the (7-9) can extract and simulate the ⌀-I curve of a ferrite material. In the following, in Section 4, the ⌀-I curve for several parameters is simulated.

4. SIMULATION OF Ø-I CURVE OF A FERRITE PHASE SHIFTER CONSIDERING THE EFFECT OF SEVERAL PARAMETERS TOLERANCES

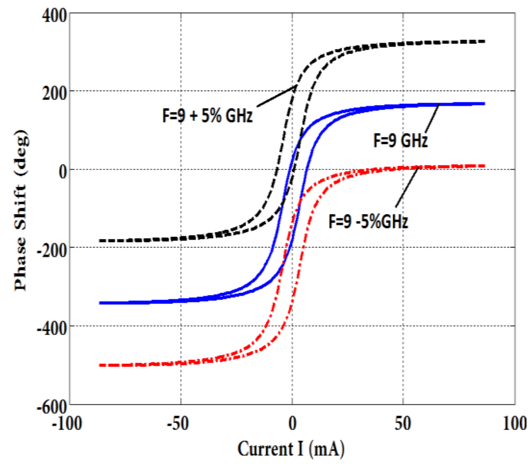
Ferrite phase shifters are often used in a communication system in multiple sets, such as in a phased array radar. A production lot of phase shifters will exhibit similar, but not identical, hysteresis curve of the ferrite material. The differential phase of ferrite phase shifters is influenced by both the material properties and key dimensional tolerances in the piece-parts assembled in to each structure. According to (1), among their material properties can indicate, permeability of the ferrite(μ) that according to (4) is dependent on frequency and magnetic moment,which it is dependent on temperature; and dielectric constant of ferrite(ε) which can vary from piece to piece during manufacturing. Also among the key dimensional tolerances can indicate, length tolerances of the ferrite rod, during manufacturing. In the Fig. 5, the ø-I curves for dielectric constant of ferrite, length of the ferrite rod, frequency and operating ambient temperature tolerances are simulated.



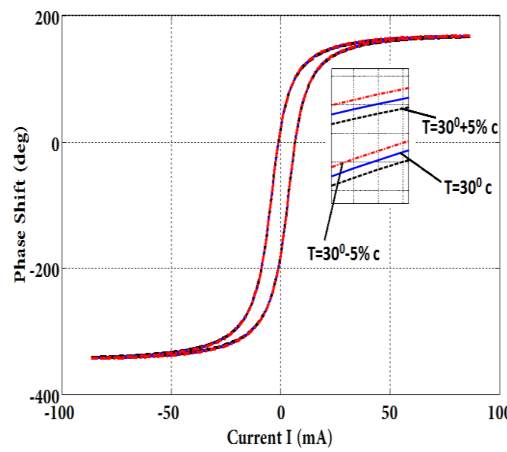
(a)



(b)



(c)



(d)

Fig. 5. Current -Phase shift curve for several parameters tolerances, Based on change in the (a) dielectric constant as much as 5%; (b) length of the ferrite rod as much as 5%; (c) frequency as much as 5%;(d) temperature as much as 5%.

According to Fig. 5, the simulations results show,the above parameters tolerances will cause the hysteresis curve tolerances. Table 2 shows the mean absolute phase change for ±5% change of investigated parameters in Fig. 5.

Table 2. The mean absolute phase change of ±5% change of investigated parameters in Fig. 5

parameter	The mean absolute phase change
dielectric constant of ferrite	78.9º c
length of ferrite rod	157.7º c
frequency	158.5º c
operating ambient temperature	0.05º c

According to Fig.5 and Table 2, we can realize that ambient temperature tolerances causes low hysteresis curve change, and length of the ferrite rod and frequency tolerances cause high hysteresis curve change in a ferrite phase shifter.

5. APPENDIX

1. $1 Wb/m^2 = 10^4$ G
2. 1G/Oe $= 4\pi \times 10^{-7}$ Wb/mA

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