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Research Article

MM-Wave Metamaterial Adjustable Antenna on Magnetically Biased Ferritic Substrate

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The paper presents a mm-wave metamaterial coplanar waveguide (CPW) zeroth-order resonating (ZOR) antenna on magnetically biased ferrite substrate. The measurements demonstrate tuning of the resonant frequency and steering of the radiation characteristic depending on the strength of biasing magnetic field. The resonant frequency shifts about 1.1 GHz for magnetic biasing field strength variation between 0 T and 0.265 T. The return loss is reduced as result of elimination of ferrite low field loss. The radiation characteristic in transversal plane steers between approximately −15° and +14° depending on the magnetic field strength. In the magnetically unbiased state the antenna gain is 4.16 dBi and increases slightly to 4.22 dBi due to small field loss reduction following the magnetic polarization application.

1. Introduction

In recent years area of metamaterials has been getting a lot of attention from the scientific community. Although Veselago enunciated the theory of left-handed (LH) materials more than 50 years ago [1], structures mimicking these properties were developed only about 12 years ago [2].

In the microwave and mm-wave frequency domain, metamaterials were introduced as the concept of composite right/left-handed transmission lines (CRLH-TL) [3]. Such a transmission line exhibits both right-handed (RH) and left-handed (LH) behavior depending on the frequency domain. This particular frequency characteristic of the CRLH-TL has been exploited in the development of many types of microwave and mm-wave devices, among them various types of antennas. A comprehensive description of the most practical leaky wave and zeroth-order resonating (ZOR) antennas was done in [4].

A special class of microwave and millimeter wave CRLH components consists of devices supported on magnetically biased ferrite. In literature there are very few contributions concerning this class of devices. A metamaterial antenna on magnetically biased ferritic material in microwave frequency domain ($f = 13.5$ GHz), demonstrating tuning capabilities of $\Delta f = 450$ MHz and a radiation lobe steering of about ±10° was reported in literature [5–7].

Based on this previous experience we present the properties of a CRLH coplanar waveguide (CPW) ZOR antenna in the mm-wave frequency domain (30 GHz), having magnetically biased ferrite as substrate. This is, upon the authors' knowledge, the first millimeter wave CRLH antenna on ferrite substrate reported for effective use in mm-wave integrated circuits.

2. Resonant CRLH Antenna Structure

The analyzed device is a ZOR CRLH antenna composed of an open-ended array of three CPW CRLH cells, each having a T circuit topology made of two series connected CPW interdigital capacitors and two parallel connected short-ended CPW inductive transmission lines. The CPW configuration was preferred due to an easier technological approach and also due to a straightforward measurement procedure using an on-wafer characterization facility. Compared with microstrip, the CPW allows a smaller circuit area because here large patch area capacitance used to connect the inductance to the ground is not necessary. Also, the vias to the ground are avoided that simplify the technological processing.

The layout of a CRLH cell and its equivalent circuit are presented in Figures 1(a) and 1(b) respectively, using symbols and notations usual in literature [4].

The starting point in the design of the CRLH cell is to choose the capacitor and inductor values to satisfy in the same time the condition of desired resonant frequency (1) that is the parallel resonance due to the two CPW short-ended transmission lines and condition (2) of balanced CRLH cell:

$$f_{\text{sh}} = \frac{1}{2\pi\sqrt{L_L C_R}}, \tag{1}$$

$$f_{\text{se}} = \frac{1}{2\pi\sqrt{L_R C_L}} = f_{\text{sh}}, \tag{2}$$

where

$$f_L = \frac{1}{2\pi\sqrt{L_L C_L}}, \qquad f_R = \frac{1}{2\pi\sqrt{L_R C_R}} \tag{3}$$

with the condition

$$f_L < f_{\text{sh}} < f_{\text{se}} < f_R. \tag{4}$$

The length of the capacitor layout is chosen so that the overall length of the CRLH cell, **p**, be much smaller comparing to the operating wavelength and taking into account, also, some technological limitations.

In this contribution CRLH cells were designed as a balanced structure for a resonant frequency $f_{\text{sh}} = 30$ GHz. The values of the elements of the CRLH equivalent circuit have been computed for $Z_C = 50\,\Omega$. These values (see Figure 1(b)) are $C_L = 460$ fF, $L_L = 0.17$ nH, $C_R = 168$ fF, and $L_R = 0.06$ nH. The computed resonant frequencies for these values are $f_{\text{sh}} = 29.78$ GHz and $f_{\text{se}} = 30.29$ GHz, defining an almost balanced CRLH structure. It may also be noticed that f_L and f_R computed with (3) fulfill condition (4).

The layout of the CRLH antenna radiating structure in CPW configuration cell was designed using IE3D-Zeland software using as substrate a ferrite wafer with the permittivity $\varepsilon_{\text{fer}} = 13.5$. With this, the following dimensions of CRLH cell layout were obtained:

(i) for the inductive CPW stub, $l_L = 230\,\mu$m, $w_L = 40\,\mu$m, and $s_L = 18\,\mu$m;

(ii) for the interdigital capacitors, $w_C = 10\,\mu$m, $s_C = 5\,\mu$m, $l_C = 250\,\mu$m, and $g_C = 65\,\mu$m, the number of digits being 10.

The length of the CRLH cell is $p = 690\,\mu$m fulfilling the condition $p < \lambda_g$ where $\lambda_g = 10,000\,\mu$m is the wavelength at $f = 30$ GHz. The antenna feeder is a 3400 μm length CPW line with the geometry computed to match the $Z_C = 50\,\Omega$ characteristic impedance of the mm-wave circuit.

Antenna was processed on a G84SK type polycrystalline ferrite wafer of 1.2 mm thick/22 mm diameter having the saturation magnetization $M_S = 0.084$ T, permittivity $\varepsilon = 13.5$, and the resonance line width $\Delta H = 16.8$ kA/m.

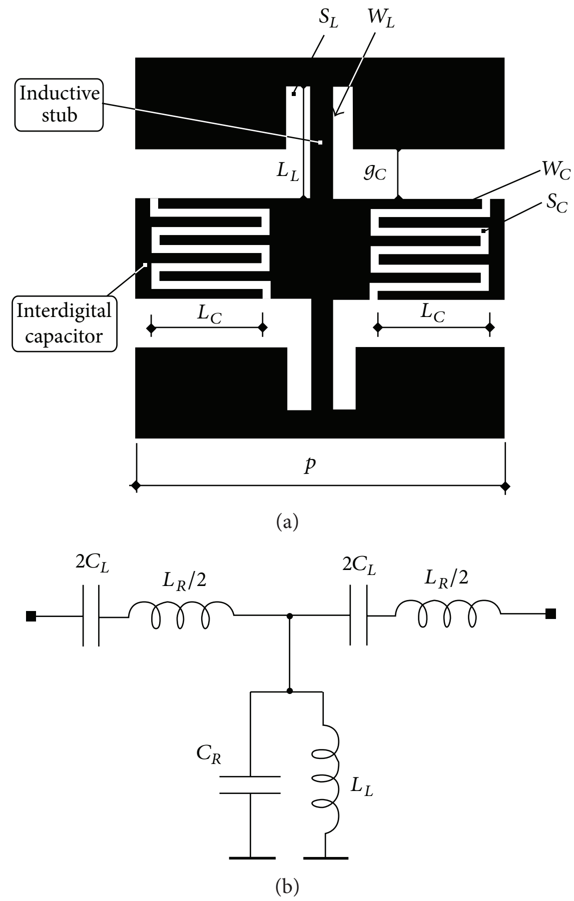


Figure 1: CPW CRLH elementary cell used in ZOR antenna construction: cell layout (a) and the equivalent circuit (b).

The wafer surface to be metalized was mirror-polished. Antenna layout was designed considering the absence of the biasing magnetic field ($H_{\text{appl}} = 0$ T) when the ferrite acts as an isotropic substrate with a relative permeability $\mu_r = 1$. When the biasing magnetic field is applied, the ferritic medium becomes anisotropic, having an effective permeability $\mu_{\text{eff}} \neq 1$. The effective permeability depends on the values of the Polder tensor that describe the electromagnetic waves propagation through a magnetically biased ferritic medium (cf [8]). For a biasing magnetic field applied normally on the ferrite substrate, the effective permeability μ_{eff} of the magnetically biased ferrite substrate was computed using the following relations (cf. [8]):

$$\mu_{\text{eff}} = \frac{{\mu'}^2 - {K'}^2}{\mu'}, \tag{5}$$

where

$$\mu' = 1 + \frac{\omega_M \omega_L \left[\omega_L^2 - \omega^2\left(1 - \alpha^2\right)\right]}{\left[\omega_L^2 - \omega^2\left(1 + \alpha^2\right)\right]^2 + 4\omega^2\omega_L^2\alpha^2},$$
$$K' = \frac{\omega_M \omega\left[\omega_L^2 - \omega^2\left(1 + \alpha^2\right)\right]}{\left[\omega_L^2 - \omega^2\left(1 + \alpha^2\right)\right]^2 + 4\omega^2\omega_L^2\alpha^2}, \tag{6}$$

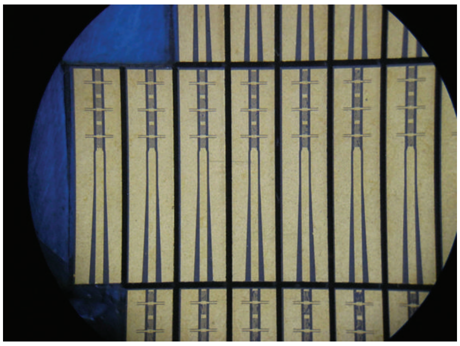


Figure 2: Processed ferrite substrate supporting antenna structures ready to be used in the return loss and resonant frequency measurements.

where

$$\gamma \left| M_S \right| = \omega_M, \qquad \gamma \left| H_i \right| = \omega L, \qquad \alpha \cong \frac{\Delta H}{2H_i}. \qquad (7)$$

For a thin wafer with the biasing magnetic field normally on its surface, as in our case, the internal magnetic field is done by

$$H_i = H_{\text{appl}} - M_S. \qquad (8)$$

3. Technological Approach

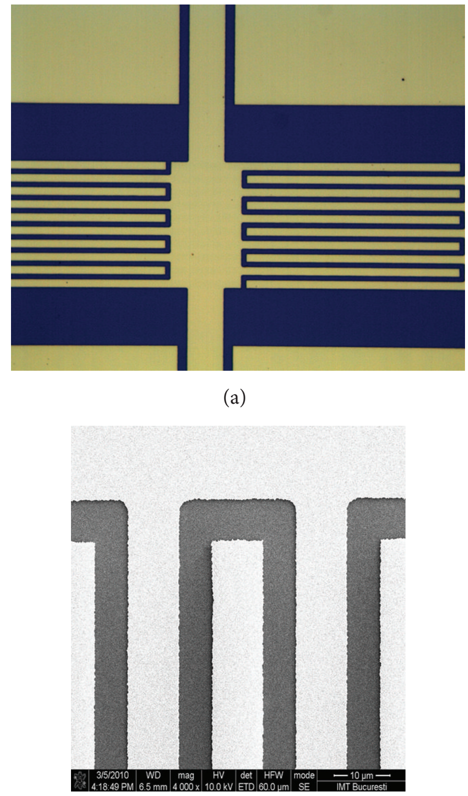
The CRLH antenna structures were processed using one mask standard positive photolithography. A metallic system made of 500 Å chromium adherence layer followed by 0.6 μm gold conducting layer was deposited by evaporation on the mirror polished side of the ferrite wafer. After processing, the CRLH antenna structures, as is shown in Figure 2, were obtained.

A microscope photo showing the configuration of the interdigital capacitors and part of the inductor lines is given in Figure 3(a). In Figure 3(b) a scanning electron microscopy (SEM) image is presented showing a detail of an interdigital capacitor.

The surface occupied by the radiant antenna structure is approx. 1.68 mm^2. To compare, a $\lambda/2$ microstrip patch antenna designed on the same kind of substrate and working on the fundamental mode at the same resonant frequency has a surface of approx. 3.17 mm^2. One may see that the CRLH antenna allows a surface size reduction of approximately 53% that is very important in the management of the mm-wave circuit planar dimensions.

At this step, the resonant frequency and the return loss were on-wafer measured with a setup consisting of an ANRITSU 37397D Vector Network Analyzer (VNA) with a 110 GHz maximum working frequency combined with a PM5 on-wafer characterization equipment from Süss Microtec. In order to magnetically bias the ferritic substrate, an electromagnet, specially designed to accommodate with the Süss Microtec equipment, was used.

A photo showing a Süss Microtec probe-tip contacting one of the antenna structures supported by the ferrite wafer is shown in Figure 4(a). The polar piece of the electromagnet providing the applied magnetic field mounted on



(a)

(b)

Figure 3: Configuration of the active part of the CRLH antenna—interdigital capacitors and part of the inductor lines—(a) and a SEM image showing a detail of an interdigital capacitor (b).

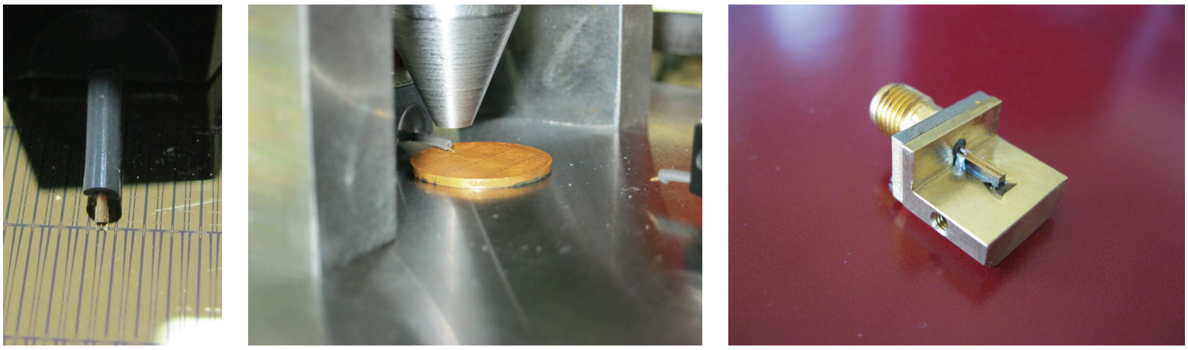
Süss Microtec measuring equipment is visible in photo in Figure 4(b). In order to measure the applied magnetic field, a Hall probe was put close to the fixed armature but it does not appear in the photos in Figure 4.

The antenna radiation characteristic and gain were measured using separate antenna structures, diced from the ferrite wafer with an abrasive diamond wheel dicing tool. Such an antenna structure mounted on a dedicated test fixture is presented in Figure 4(c).

4. Functional Parameters of the CRLH Antenna

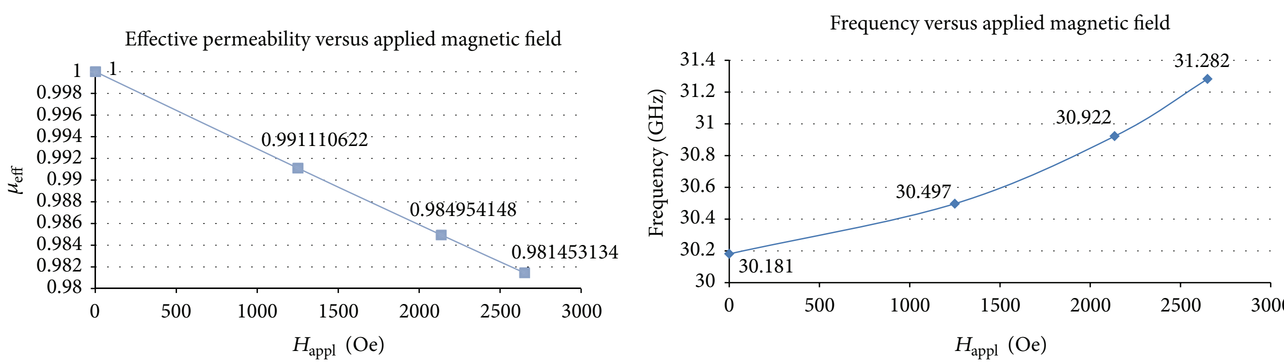
4.1. Resonant Frequency and Return Loss. Computations made using the above (5)–(8) relationship show that for a frequency $f \cong 30$ GHz, with the applied magnetic field strength sweeping from $H_{\text{appl}} = 0$ T to $H_{\text{appl}} = 0.265$ T, the effective permeability of the ferrite substrate decreased from $\mu_{\text{eff}} = 1$ to $\mu_{\text{eff}} \cong 0.98$ as it is shown in graph in Figure 5(a). Due to this decrease, the computed resonant frequency of the CRLH antenna increases from approx. 30.18 GHz to approx. 31.3 GHz as is shown in graph in Figure 5(b).

The measured result of antenna resonant frequency and return loss following the ferrite substrate biasing with magnetic field is summarized in Table 1 and is shown in Figure 6.



(a) (b) (c)

Figure 4: Süss Microtec probe-tip contacting a CRLH antenna structure supported by the ferrite wafer (a), the electromagnet providing the magnetic biasing field (b), and one of the antenna structures mounted on a test fixture (c).



(a) (b)

Figure 5: (a) Computed variation of the effective permeability μ_{eff} (a) and of the antenna resonant frequency (b) following the sweep of the applied magnetic field from $H_{\text{appl}} = 0$ T to $H_{\text{appl}} = 0.265$ T.

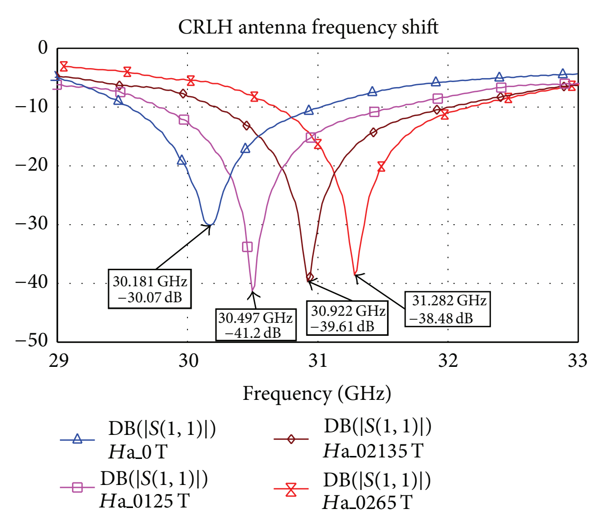


Figure 6: Antenna resonant frequency following the biasing magnetic field variation.

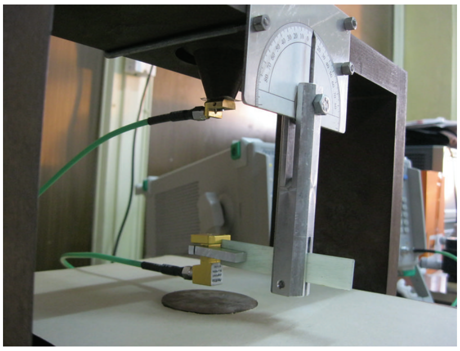
From Figure 6 as well as from Table 1 it can be seen that in absence of magnetic biasing field the measured return loss shows $S_{11} = -30.07$ dB at $f = 30.181$ GHz. If a magnetic biasing field with an increasing strength from $H_{\text{appl}} = 0$ T to $H_{\text{appl}} = 0.265$ T is applied, the frequency, also, gradually increases from the initial value $f = 30.181$ GHz to higher values up to $f = 31.282$ GHz. The return loss, also, decreases from $|S_{11}| = 30.07$ dB for $H_{\text{appl}} = 0$ T to $|S_{11}| = 41.2$ dB for $H_{\text{appl}} = 0.125$ T.

Table 1: Return loss and resonant frequency shift as result of ferrite substrate magnetic biasing.

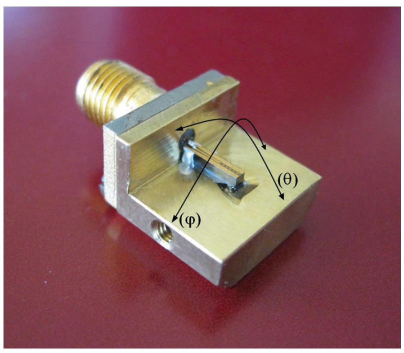
H_{appl} (T)	Frequency (GHz)	S_{11} (dB)
0	30.181	−30.07
0.125	30.497	−41.2
0.2135	30.922	−39.61
0.265	31.282	−38.48

The reduced value of S_{11} graph for $H_{\text{appl}} = 0$ T are due to the low field loss in ferrite medium in absence of the biasing magnetic field.

4.2. Radiation Characteristic. The radiation characteristic was measured using an experimental setup that allows magnetically biasing the ferrite substrate. An image of this experimental arrangement for radiation lobe measurement in



(a)



(b)

Figure 7: Experimental setup dedicated to CRLH antenna radiation characteristic in transversal plane (a) and definition of the measurement planes (b).

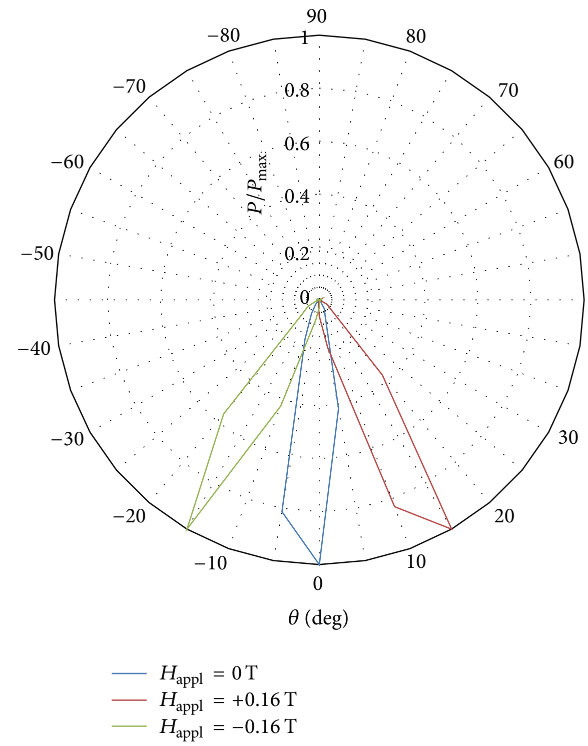


Figure 8: Steering of the antenna radiation characteristic in the transversal plane (φ) depending on the applied biasing magnetic field.

transversal plane (φ) is shown in Figure 7(a). The same setup slightly modified was used to measure the radiation lobe in longitudinal plane (θ). For the definition of transversal (φ) and longitudinal (θ) measurement planes, see Figure 7(b).

The CRLH antenna fixed on the electromagnet polar piece was used as emitting device. It was fed from an Agilent E8527D generator as a signal source. As receiving device was used a waveguide aperture of an Anritsu 35WR28KF waveguide-coaxial transition. The received signal was displayed on an Anritsu MS2668C spectrum analyzer. The experimental arrangement allows the waveguide aperture to rotate around the emitting CRLH antenna to be measured, both in transversal (φ) and longitudinal (θ) planes. In both planes the measurements were carried out with and without magnetic biasing field, following results being obtained.

Radiation characteristic in the transversal plane (φ) is presented in Figure 8. The graphs were obtained by normalising the power at a current angle to the maximum obtained power. In absence of the biasing magnetic field, the radiation characteristic have its maximum at 0° and the −3 dB lobe width is 11°. For different strengths of the applied magnetic field in the domain $H_{appl} = \pm 0.16$ T the radiation lobe steer between approx. $+14^\circ$ and -15° is presented in Figure 8.

Measurement of radiation characteristic in CRLH antenna longitudinal plane (θ) was made with the setup shown in Figure 7(b), slightly modified to allow Anritsu 35WR28KF receiving waveguide to rotate from back to forward direction. Related to center of the antenna radiating structure, the sign (−) was assigned for the angles toward back of antenna (toward the connector) and the sign (+) was assigned for the angles toward front of antenna.

The experimental results are shown in Figure 9 where was plotted the radiated power at different angles in the (θ) plane for biasing magnetic field $H_{appl} = 0$ T and $H_{appl} = 0.16$ T. All data were rated at the maximum power value obtained for an angular sweep between $\theta = -85^\circ$ and $\theta = 90^\circ$. From Figure 9 one may find that the maximum radiated power occurs at an angle $\theta \cong 30^\circ$ in the forward direction, regardless of magnetic biasing of the ferritic substrate. Also, an increase of the radiated power following magnetically biasing of the device as effect of elimination of the low field losses in ferrite substrate may be observed. The maximum radiated power remains at $\theta \cong 30^\circ$.

4.3. Antenna Gain. Antenna gain was measured using De Friis relation for both magnetically unbiased and biased states of the ferrite substrate, using two identical CRLH antennas. Due to technical reasons the biasing magnetic field was applied only to the emitting device. The following formula derived from De Friis relation was used:

$$G\ (\text{dBi}) = 10 \log_{10} \left(\frac{4\pi R}{\lambda} \sqrt{\frac{P_r}{P_t}} \right), \tag{9}$$

where λ = wavelength at the measuring frequency (for f = 30 GHz the wavelength is λ = 10 mm), R = distance between

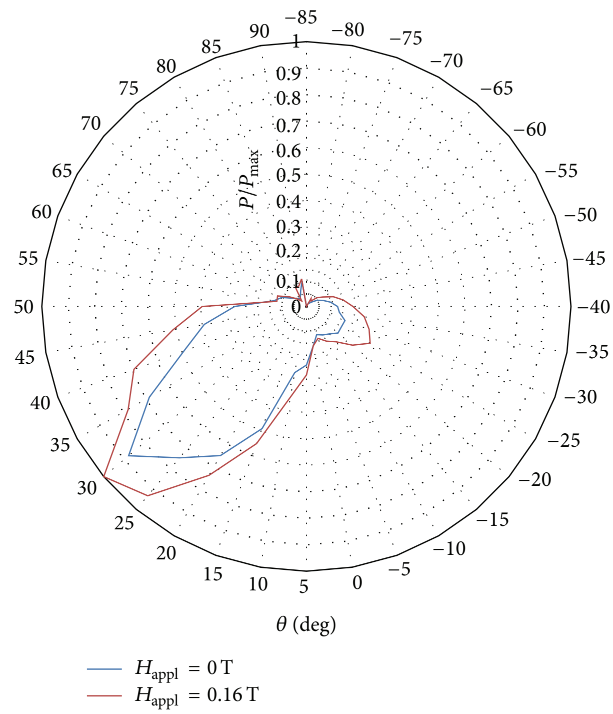


FIGURE 9: Radiation characteristic of the CRLH antenna on ferrite with and without magnetic biasing field.

emitting and receiving antennas ($R = 100$ mm was chosen in order to accomplish the far field condition at the working frequency), and P_t and P_r are power transmitted by emitting antenna and power at the receiving antenna, respectively. In our measurement $P_t = 0.01$ mW and $P_r = 3.87 \times 10^{-5}$ mW.

Initially, gain was measured without biasing magnetic field, $H_{appl} = 0$ T. In this condition, using previously measured values the gain of the emitting antenna in this magnetic unbiased state was $G_{i,0} = 4.16$ dBi. If a biasing magnetic field with the strength $H_{appl} = 0.160$ T is applied, all the experimental arrangement remaining unchanged, a value of the gain $G_{i,mag} = 4.22$ dBi was found. This slight gain increase is due to the ferrite low field loss reduction following magnetic biasing.

It is to note that in magnetically biased state the maximum of radiation characteristic of the emitting antenna is no more in the direction $\varphi = 0^\circ$ but in the direction $\varphi \cong 15^\circ$ in the transversal plane. In this situation attention was paid to the proper alignment of the emitting antenna so that the radiation lobe has its maximum aligned normally on the surface of the receiving antenna; all the remaining parameters remaining unchanged.

5. Conclusion

In this contribution we present a CRLH CPW ZOR antenna having a magnetically polarized ferrite as supporting substrate. The experimental data shows the following.

(a) A frequency shift of about 1.1 GHz occurs, between 30.181 GHz and 31.282 GHz, due to the variation of the effective permeability of the ferrite substrate following the magnetic biasing. The measured frequency shift is consistent with the calculated values for three magnetic biasing field strengths.

(b) The antenna radiation lobe has a beamwidth of approx. 11° and steer in the domain −15°–+14° for a biasing magnetic field $H_{appl} = \pm 0.160$ T.

(c) The longitudinal radiation characteristic is squinted in the antenna forward-edge direction with an angle of about 300. The applied biasing magnetic field has no influence on this squinting angle.

(d) Antenna gain is $G_{i,0} = 4.16$ dBi at the frequency $f = 30$ GHz and magnetically unbiased state and increase to $G_{i,mag} = 4.22$ dBi when a biasing magnetic field $H_{appl} = 0.160$ T is applied.

(e) Elimination of the small field losses can be seen as a result of magnetic polarisation of the ferritic substrate. This effect is visible in slight increase of antenna gain and of the longitudinal radiation lobe amplitude when the biasing magnetic field is applied.

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