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X-band phased array antennas using crystal yttrium–iron–garnet phase shifters

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X-band phased array antenna containing four linear microstrip patch elements has been fabricated and tested. The elements were fed through single-crystal yttrium–iron–garnet phase shifters. By varying the bias magnetic field the input phases to the antenna elements can thus be tuned, resulting in steering of the radiation beam in one dimension. © 2000 American Institute of Physics. [S0021-8979(00)49508-3]

I. INTRODUCTION

Present-day research into electronically steered phased array antennas has shown that high costs, susceptibility to damage, repairability, and so on, are problematical issues that will remain in the immediate future. There is considerable interest in developing simpler, more robust technologies to increase reliability and lower costs. To this end we have fabricated a linear phased array antenna at X band using crystal yttrium–iron–garnet (YIG) as the frequency agile material adjusting the input phase of the elements. The array contains four square patches, connected to four stripline feeders with equal power. The feeders include YIG phase shifters whose output phases can be progressively varied via an external magnetic field applied normal to the array substrate. This results in steering of the radiation beam in one dimension.

Difficulty in using a ferrite substrate at X-band frequencies is that the bias magnetic field requires a magnitude at least several thousand oersteds to effectively change the permeability of the substrate. In order to practically use a ferrite substrate the bias field is thus divided in two parts: the permanent part and the variable part. The permanent part of the bias field is furnished by using a permanent magnet, providing a constant background for magnetic biasing. The variable bias field is then superimposed to the permanent part, resulting in local variation of the bias field near its permanent field value. The variable field requires only a small magnitude in comparison to the permanent field, which can then be conveniently obtained by using a solenoid coil.

In order to reduce the bias current in the solenoid coil, and hence, to enhance the switching speed of the phase shifter device and to lower power dissipation, the magnitude of the variable bias field shall be kept as a minimum. For this purpose we desire to operate a ferrite phase shifter near ferromagnetic resonance (FMR). In the vicinity of FMR the

permeability of the ferrite material is a sensitive function of the bias field, and a slight change in the bias field can result in a significant change in permeability.¹ However, the price to pay is that when FMR is approached, wave propagation in the ferrite material becomes very lossy. To overcome this difficulty we have demonstrated in a previous article that it is possible to operate a ferrite phase shifter near FMR without experiencing much magnetic loss if the ferrite material exhibits a narrow FMR linewidth.²

Due to the very narrow FMR linewidth of single-crystal YIG it is an ideal material to be used for microwave phase-shifter devices at X band. The linewidth of single-crystal YIG is about 0.5 Oe at X band. In Ref. 2 we have reported the performance of an X-band stripline phase shifter using single-crystal YIG thick films as the substrate material. We found that² at 10 GHz the phase shifter, which is of a quarter-wave length in the absence of a bias magnetic field, produced a phase change of 120° in the transmitted signal when the internal field was varied from 3440 to 3720 Oe. The accompanying change in insertion loss was from 0.5 to 0.4 dB.

In this article we report the performance of a phased array at X band using single-crystal YIG phase shifters as the phase tuning elements. The array contains four linear rectangular microstrip patches. We found that sensitive beam steering occurs near FMR at 4750 Oe of the applied magnetic field. However, useful radiation patterns result only when the YIG material is biased at the knee above FMR giving rise to narrow-beam radiation with insignificant attenuation (or large radiation efficiency). This corresponds to about a beam-steering angle of 15° for the bias field varying from 4920 to 5270 Oe. Larger steering angles are obtainable if longer phase shifter lines are used.

II. RESULTS

Figure 1 shows the layout of the fabricated antenna array. In Fig. 1 six regions are distinguished. Region I is of a

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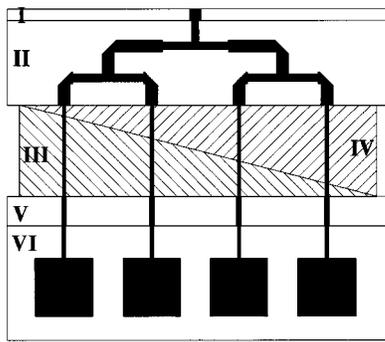


FIG. 1. Layout of the phased array antenna.

width 2.5 in. and a length 0.0764 in., containing a stripline of impedance 50Ω using air as the substrate/superstrate material. The stripline is connected to a coax (OSM) launcher for microwave input. Region II, $2.5 \times 0.570 \text{ in.}^2$, contains stripline power splitters, and the input microwave power is divided into four equal parts with little reflection. In region II duroid (dielectric constant 2.2, thickness 0.031 in.; Rogers, Chandler, AZ) is used as the substrate/superstrate material. Region V, $2.5 \times 0.199 \text{ in.}^2$, includes four stripline transformers using the same duroid material as the substrate and the superstrate, and region VI, $2.5 \times 0.75 \text{ in.}^2$, contains four microstrip patches attached with feeders deposited on the same piece of the substrate extended from region V. No superstrate is used in region VI, radiating energy away from the antennas allowing measurements to be taken directly above region VI. The microstrip patches are of a square geometry with dimension $0.388 \times 0.388 \text{ in.}^2$. The stripline/microstrip circuit as well as the six regions shown in Fig. 1 has been drawn in scale.

In Fig. 1 region IV contains frequency agile material used to construct stripline phase shifters, and region III is for phase compensation. That is, we require these two regions to have the same dielectric constant so that equal phase results at the input of the patch antennas in the absence of a bias magnetic field. The boundary between regions VI and III is linearly tapered so as to provide progressive phase changes when the permeability of the substrate/superstrate of region IV is varied. A bias field is applied normal to the substrate/superstrate surface, whose magnitude can be varied from 4000 to 8000 Oe. The magnetic field is supplied by using a pair of neodymium permanent magnets ($2 \times 2 \times 1 \text{ in.}^3$) and the bias field can be varied by adjusting the gap distance of the yoke separation. The dielectric constant of the dielectric material used in region III is 14 (Trans Tech, Adamstown, MD). The dimension of region III plus region IV is $2 \times 0.616 \text{ in.}^2$.

In region IV we use single-crystal YIG/GGG/YIG as the frequency agile material. The YIG/GGG/YIG material was purchased from Airtron, Charlotte, NC. The YIG films are of a nominal thickness of $100 \mu\text{m}$, which were epitaxially grown along the $\langle 111 \rangle$ direction on both sides of a crystal GGG substrate (thickness 20 ml and dielectric constant 14.7). The YIG films are characterized by the following parameters: saturation magnetization $4\pi M_s = 1750 \text{ G}$, dielectric constant $\epsilon_f = 14.7$, anisotropy field $H_A = 82 \text{ Oe}$, and an

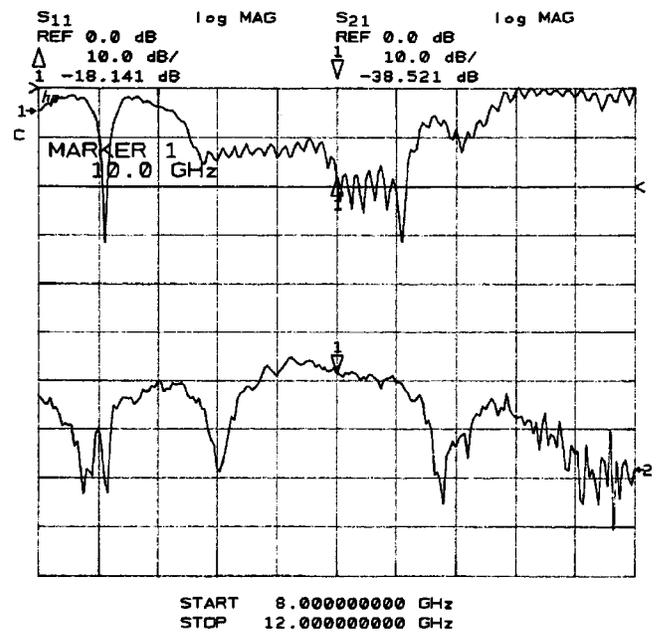


FIG. 2. The measured reflection, S_{11} , and transmission, S_{21} , data of the fabricated phased array antenna.

FMR linewidth $\Delta H \approx 0.5 \text{ Oe}$ at 10 GHz. The dielectric loss tangent for both YIG and GGG materials is 0.0002.

The circuit of Fig. 1 was characterized using a vector network analyzer, HP-8510B. As shown in Fig. 2 the reflection data, S_{11} , indicate that the fabricated antenna array is of a bandwidth extending from 9.1 to 10.5 GHz. The transmission data, S_{21} , was measured using a waveguide horn antenna placed 5 ft above the antenna array. No shielding was applied during the transmission measurement and the measured S_{21} data of Fig. 2 include multiple-path effect.³

The radiation pattern of the antenna array was measured in an anechoic chamber located at Rome Laboratory, Hanscom, MA. The properties of the measured main-beam radiation are summarized in Fig. 3, where the location, the intensity, and the beamwidth, are plotted as a function of the applied bias-field strength, H_0 . From Fig. 3 it is seen that useful radiation occurs when the bias field H_0 is varied from 4920 to 5270 Oe, resulting in a beam steering angle of 15°

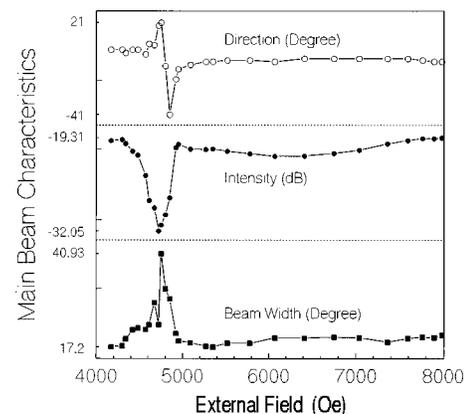


FIG. 3. Measured main-beam properties plotted as a function of the external bias field: beam direction, intensity, and beamwidth.

without causing much beam broadening and attenuation (less than 1 dB). The measured radiation patterns at various bias-field strength together with theoretical calculations will appear elsewhere.⁴

III. CONCLUSIONS

We conclude that practical phased array antennas operating at X band can be fabricated using single-crystal YIG material characterized by a narrow FMR linewidth. While the transmission phase can be sensitively tuned by applying a bias magnetic field, the insertion loss through the phase shifters can be retained at a relatively constant low level. In addition, it is necessary to bias the YIG-film material with a small variable field of magnitude ± 100 Oe, which can be obtained using a solenoid coil.

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