An Active Module Using a Ferroelectric CPW Phase Shifter for a Ku-Band APAA System

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This paper presents the development of an active module using a ferroelectric coplanar waveguide (CPW) phase shifter for a Ku-band active phased array antenna (APAA). This active module performs roles such as amplifying an RF signal with low noise coming from an antenna and changing the phase of a received RF signal. This module is composed of a 3-stage low-noise amplifier (LNA), a high-voltage dc block with an RF choke (RFC), and a ferroelectric phase shifter, whose structure is a CPW transmission line based on a (Ba, Sr)TiO$_3$ (BST) thin film. The ferroelectric BST thin film is deposited on an MgO substrate by using pulsed laser deposition. Both ends of the CPW are continuously tapered to obtain good impedance matching without degrading the phase tuning property of the ferroelectric CPW phase shifter. The active module using a ferroelectric CPW phase shifter attains a phase-controllable range of 360° while retaining a return loss of better than –15 dB at Ku-band. The measured gain of the active module increases from 2 dB to 16 dB corresponding to a change in the dc voltage from 0 to 150 V with a 3.6 dB maximum noise figure at 12 GHz.

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I. INTRODUCTION

Satellite communications have grown rapidly in the last few decades because terrestrial communications cannot provide complete coverage within a large global region. The phased array antenna is absolutely needed to receive a signal directly for mobile satellite communication. Each radiating element of a phased array is normally associated with a phase shifter (or an active module) with which the element phase can be varied through 360°, and the phase shifter (or the active module) with its beam steering control circuitry accounts for the main hardware cost of a phased array antenna [1].

This paper presents an active module using a ferroelectric phase shifter for realizing a low-cost phased array antenna. Ferroelectric phase shifters have many advantages, such as small size, simple process for making the device, low power consumption, high power transmission capability, fast response time, and simple beam steering control at low cost [2–6].

Although there are several designs for ferroelectric phase shifters, the coplanar waveguide (CPW) transmission line is used for an active module because the CPW is compatible with monolithic fabrication techniques and uses only one side of the substrate, so the costly through-substrate via-hole process can be eliminated, which results in low cost and simple process. In designing a ferroelectric CPW phase shifter, we use the external impedance matching networks at both ends of the CPW for the impedance matching of the CPW while maintaining the phase tuning property because the two characteristics of the CPW are oppositely influenced by the geometrical dimensions of the CPW [7–9].

In this paper, we describe the design of an active module composed of the above ferroelectric CPW phase shifter and a low noise amplifier (LNA). In this research, we investigate an active module using a low-cost ferroelectric CPW phase shifter.

II. EXPERIMENTAL PROCEDURE

Single-phase (Ba$_{0.6}$Sr$_{0.4}$)TiO$_3$ (BST) films were deposited on MgO substrates by using pulsed laser deposition.
Fig. 1. $\theta$-2$\theta$ XRD pattern of the BST film deposited on a (001) MgO substrate. The inset in the figure shows a rocking curve of the (002) peak of BST.

Fig. 2. Block Diagram of the active module using a ferroelectric CPW phase shifter.

Fig. 3. Photograph of the complete active module using a ferroelectric CPW phase shifter.

III. ACTIVE MODULE DESIGN

The active module using a ferroelectric CPW phase shifter was designed to steer the beam of the array antenna with low noise power amplification for satellite signal reception in a mobile communication system. A block diagram of the module is shown in Fig. 2. The module consists of three subassemblies: a low noise amplifier (LNA), a high-voltage dc block with RFC, and a ferroelectric CPW phase shifter. The photograph of the complete active module using a ferroelectric CPW phase shifter is shown in Fig. 3.

The LNA consists of three stages of low-noise amplification using low noise hetero junction FETs to achieve an excellent low noise and associated gain which make it suitable for a satellite communication system. In the LNA design, there are four performance factors that must be considered: noise figure, available power gain, power output, and input and output matching. Because the total noise figure of the LNA is basically determined by the noise figure of the first stage of the LNA, the first
stage of the LNA was designed to minimize the noise figure above all. The second and the third stages of the LNA were designed for high gain [15]. The linear bias condition of $V_{ds} = 2 \text{ V}$ and $I_{ds} = 10 \text{ mA}$ provides a good compromise between the minimum noise figure bias point and the maximum gain bias point. The overall design of the LNA with matching networks was carried out to obtain optimized component values for the desired noise figure, gain, and matching performances by using an RF circuit simulator. The FET bias controller was used to meet the bias requirements of the LNA with a minimum of external components. An attenuator was inserted between the second and the third stages of the LNA to stabilize the total characteristics of the LNA.

A series capacitor was used to isolate the bias voltage applied to each stage of LNA and to block the dc voltage while allowing the RF signal to pass through with minimal loss. The capacitor is capable of only a few voltages. To apply a high dc voltage dc to the ferroelectric CPW phase shifter up to 200 V and to prevent the high dc voltage from affecting another subassembly, we used a coupled-line dc block. A coupled-line section with open circuit termination operates like a one-pole band-pass filter (BPF) and provides the required characteristics, a high-voltage dc block and low loss, for the ferroelectric CPW phase shifter over a wide frequency range. When the bias voltage is applied to the ferroelectric CPW phase shifter, the RF energy should not leak out through the bias port, so the RF choke is realized by using a high-impedance $\lambda/4$ line terminated with a radial stub [16]. The structure was analyzed and optimized by using an electro-magnetic simulator.

In designing the ferroelectric CPW phase shifter, the geometrical dimensions of the CPW and the physical values for the materials are important. The relative dielectric constant of the BST film was extracted from the capacitances of the BST IDC by using the conformal mapping and was about 1000 at Ku-band with no dc bias. The thickness of the BST film, 400 nm, was chosen from the thickness-dependent saturation of the dielectric constant variation. The thickness of the MgO substrate, 0.5 mm, was chosen because of convenience. In the ferroelectric CPW phase shifter, it is hard to attain impedance matching and a large differential phase shift simultaneously because both characteristics are oppositely influenced by the geometrical dimensions of the CPW. For a large differential phase shift, the gap size should be narrow within the range of possibility because of the applied-electric-field-dependent dielectric tunability. The narrower the gap size of the CPW is, the smaller the impedance the CPW is. To increase the impedance of the CPW while having the small gap size, the width size of the CPW should be narrowed. But there is a lower limit on the width of the CPW because of the line-width limit in general photolithography and the high metal loss due to the narrow width size of the CPW. Therefore, we chose the width and gap dimensions as 10 and 10 $\mu$m, respectively to compromise between impedance matching and large differential phase shift, though the characteristic impedance of the ferroelectric CPW phase shifter is smaller than 50 $\Omega$.

To improve the loss characteristics due to the impedance mismatch with the above dimensions of the CPW, we added the impedance matching networks at both ends of the CPW. Therefore, there are two parts in the ferroelectric CPW phase shifter, an impedance matching part and an effective transmission line part. The structure of the impedance matching part was basically a CPW transmission line, which was comprised of a center signal line and two neighboring ground lines. The impedance of the input section in the impedance matching part was about 50 $\Omega$, the dimension of which was determined by considering both the dielectric constant and the thickness of the BST film and the MgO substrate, as well as the connection bead dimension in the packaging metal box. The 50 $\Omega$ ferroelectric CPW dimension in the impedance matching part was 210 $\mu$m in width and 130 $\mu$m in gap size. In the impedance matching part, the width of the center line was decreased to that of the signal line in the effective transmission line.
Fig. 5. Measured gain of the active module using a ferroelectric CPW phase shifter.

Fig. 6. Measured noise figure of the active module using a ferroelectric CPW phase shifter.

IV. RESULTS AND DISCUSSION

The active module using ferroelectric a CPW phase shifter was fabricated and tested for the Ku-band APAA system. The measured return loss and differential phase shift of the module as functions of frequency under an external dc bias voltage from 0 to 150 V are shown in Fig. 4. The active module using the ferroelectric phase shifter presented here showed a continuous 360° phase shift at the Ku-band. The return loss of the module was better than −15 dB at 12 GHz without the influence of varying the dc bias voltage. Because the impedance matching of LNA was optimized to that value, the impedance matching part of the ferroelectric CPW phase shifter was well designed.

The measured gain of the active module is shown in Fig. 5. The gain increased from 2 dB to 16 dB as the dc voltage was varied from 0 to 150 V at 12 GHz. The gain of the active module using the ferroelectric CPW phase shifter increase with the applied dc bias voltage because the insertion loss of the ferroelectric CPW phase shifter decreased as the bias voltage was increased. The gain varied linearly with frequency, which is attributed to the characteristics of the ferroelectric CPW phase shifter. Fig. 6 shows the measured noise figure (NF). The maximum NF of the active module was 3.6 dB at 12 GHz. The NF of the active module was relatively worse when the module was at the low dc bias stage because the ferroelectric CPW phase shifter, which is capable of a phase controllable range of 360°, has a large value of insertion loss at a low dc bias. In order to improve the NF characteristics of the active module using ferroelectric phase shifter, we should use a finer design of the ferroelectric phase shifter.

V. CONCLUSION

An active module using a ferroelectric CPW phase shifter is investigated for use in a Ku-band active phased array antenna (APAA) system. It consists of a low noise amplifier (LNA), a high-voltage dc block with RF choke (RFC), and a ferroelectric coplanar waveguide (CPW) phase shifter. The design of the LNA with matching networks was carried out to obtain the optimized component values in terms of the desired noise figure, the gain, and the matching performances by using an RF circuit simulator. The high-voltage dc block with RFC and the ferroelectric CPW phase shifter were analyzed and optimized by using an electro-magnetic simulator. The active module using a ferroelectric CPW phase shifter showed continuous 360° phase shifting while retaining a return loss of better than −15 dB at Ku-band. The measured gain of the active module increased from 2 dB to 16 dB with increasing dc voltage from 0 to 150 V with a 3.6 dB maximum noise figure at 12 GHz.

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