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Compact Metamaterial-Based Tunable Phase Shifter at 2.4 GHz

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Abstract

A compact metamaterial (MTM)-based tunable phase shifter consisting of four unit cells with a simple DC bias circuit has been designed at 2.4 GHz. The variable series capacitors and shunt inductors that are required to be loaded periodically onto a host transmission line are realized employing only chip variable capacitors (varactors). In addition, the proposed phase shifter requires only one DC bias source to control the varactors, with the matching condition of the MTM line automatically satisfied. The measured phase shifting range is 285.2° (from −74.2° to 211°). The measured insertion loss is approximately 1.5 dB. The circuit/electromagnetic-simulated and measured results are in good agreement.

Key Words: Metamaterials, Negative Refractive Index, Phase Shifters, Transmission Lines.

Ⅰ. Introduction

Phase shifters are key components in many microwave systems including phased-array antennas. The phase shifters have been developed using various methods such as the multi-bit switched line method, loaded line method, hybrid coupled method, and so on. More recently, an octave-band 4-bit phase shifter using discrete components has been presented [1] for a band from 530 to 1,100 MHz. It has a wide phase shifting range, but the output phases are discretely determined depending on the number of loaded line cells, with a relatively large insertion loss of about 2.7 dB. An metamaterial (MTM)-based electronically controlled transmission line (TL) structure was proposed in [2] as a leaky-wave antenna, with its phase controlled using only one bias voltage. However, since its only optimal impedance matching was sought, it has relatively large reflection coefficients near the center frequency of 3.33 GHz. In the linear phase shifter using MTM TL reported in [3] employed only series varactors, which resulted in limited impedance matching and phase shift range. An artificial line phase shifter, presented in [4], enables the separate control of phase and line impedance with three bias voltage points. Another MTM-based tunable phase shifter has been adopted for a scannable microstrip patch array antenna [5]. In it, the unit cell of the phase shifter consists of a series chip varactor and a shunt active inductor. However, the bias circuits to control the active inductor seem to be rather complicated and may possibly be avoided. In this letter, instead of the active inductor, we use a chip variable capacitor (varactor) and a simple $\lambda/4$ impedance inverter to realize a compact phase shifter. The varactor can also be designed to have the same capacitance as that on the main radio frequency (RF) line, thereby enabling the use of the same DC bias voltage for all of the varactors, with the matching condition of the MTM line automatically satisfied.

Ⅱ. Design of Tunable Metamaterial Phase Shifter Unit Cell

Fig. 1(a) shows the unit cell of the proposed MTM phase shifter, which is constructed using a microstrip line on a Teflon substrate with a relative permittivity of 2.2 and a height of 1 mm. The design frequency is 2.4 GHz. Fig. 1(b) shows the equivalent circuit of the unit cell. An MTM unit cell usually consists of a conventional host TL with an electrical length *kd*, a series lumped capacitor with a capacitance of C_0, and a shunt inductor with an inductance of L_0. For this work, the effective permittivity of the host TL is 1.78, while *kd* has been chosen to be 21° (*d*=5.3 mm) at 2.4 GHz for a compact design. C_0 and L_0 are obtained by the following convenient design equations [6],

$$C_0 = 1/\omega Z_0(kd+\phi_\omega),\ L_0 = C_0 Z_0^2. \quad (1)$$

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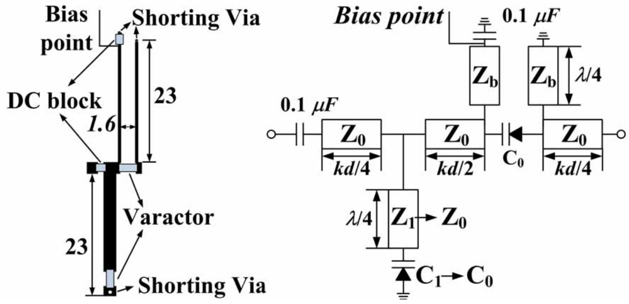


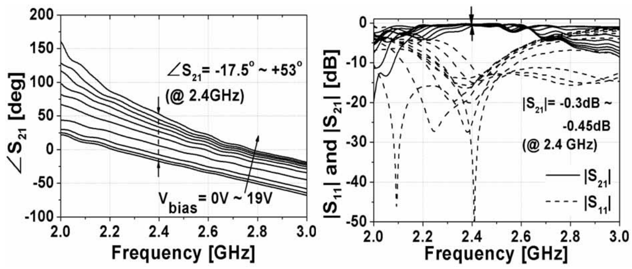
(a) (b)

Fig. 1. Metamaterial-based phase shifter unit cell with DC bias circuit. (a) Schematic (unit=mm) and (b) equivalent circuit.

Where ϕ_ω is the desired phase shift at a specific angular frequency ω, and Z_0 is the characteristic impedance of the host TL. To realize a shunt inductance L_0, we use a $\lambda/4$ impedance inverter and a varactor with C_1 determined by (2) [7],

$$C_1 = C_0 Z_0^2 / Z_1^2 . \quad (2)$$

Where Z_1 is the characteristic impedance of the impedance inverter. By choosing Z_1=Z_0, the value of C_1 becomes identical to C_0. This means that we can use only one DC voltage source to simultaneously control the series capacitance and the shunt inductance. This choice also guarantees a matching condition of the MTM line, at least for a narrowband about the design angular frequency ω_0. Z_0 has been chosen to be 84.6 Ω (line width, 1.2 mm) to ensure that the line width is adequate for mounting a chip varactor and for reduced coupling between the $\lambda/4$ impedance inverters when they are periodically loaded. The SMV1283-011LF hyper-abrupt junction varactor diode from Skyworks Solution Inc. has been selected to control the C_0 values. The recommended capacitance range of the varactor is from 14.228 pF to 0.517 pF, with the necessary reverse bias voltages from 0 V to 26 V. We restrict the use of the C_0 values from 14.228 pF (about 0 V) to 0.607 pF (about 19 V). Using this range, the phase shifts (ϕ_ω) of the MTM unit cell are from −17.5° to 53.0°. The use of phase shifts exceeding 53° by applying a DC bias voltage greater than 19 V has been found to result in relatively large insertion losses. The series resistance of the varactor is 2.4 Ω. The DC bias circuitry has been devised to simultaneously supply the same voltage to the two varactors, with two DC block capacitors with capacitances of 0.1 μF. The RF line is isolated from the DC bias lines at 2.4 GHz with shorting vias and $\lambda/4$ impedance transformers. The diameter of the shorting via is 0.3 mm. The characteristic impedance Z_b is 158 Ω (the thinnest possible). The measured $\angle S_{21}$ and $|S_{21}|$ of the phase shifter unit cell for different DC bias voltages V_{bias} from 0 V to 19 V are shown in Fig. 2, as a function of frequency. The insertion loss around 2.4 GHz is less than 1 dB. The series resistance of the varactor is a major cause of the insertion loss.



(a) (b)

Fig. 2. Measured (a) $\angle S_{21}$, (b) $|S_{11}|$ and $|S_{21}|$ of the unit cell depending on DC bias voltages from 0 V to 19 V as a function of frequency.

Ⅲ. Fabrication and Performances

Two photographs of the fabricated tunable phase shifter are shown in Fig. 3, with dimensions. The size of the phase shifter without the transformers and bias circuitry is 21.2 mm×24 mm (0.17 λ_0×0.19 λ_0). The phase shifter consists of 4 MTM unit cells and a DC voltage splitter. Under the splitter, the ground plane has been etched out to minimize its effects on the RF line. At the input and output of the phase shifter, with its characteristic impedance of 84.6 Ω, $\lambda/4$ impedance transformers with 64.6 Ω are used for the impedance matching to the input line and the subminiature version A (SMA) connector with 50 Ω. The bias splitter lines are combined to a bias pad. Fig. 4(a) shows the circuit/electromagnetic (EM)-simulated and measured magnitudes of the S-parameters at 2.4 GHz depending on the applied DC voltage in the range of 0 V to 19 V. The used varactor model in the simulations is the lumped series resistor-capacitor (RC) circuit with R=2.4 Ω and recommended capacitances. Across the entire phase tuning range, the measured $|S_{11}|$ varies from −39.6 dB to the worst case of −15 dB, and $|S_{21}|$ varies from −1.3 dB to the worst case of −1.7 dB at the two extremes. The circuit/EM-simulated and measured phases in Fig. 4(b) are in good agreement and range from −74.2° to 211°. The performance of the proposed phase shifter is compared with others in Table 1. The proposed phase shifter shows superior characteristics in terms of the phase shifting range, return/insertion losses, amplitude imbalance, control of the varactors, and simplicity of bias circuits for them. Its size is the smallest among currently proposed MTM-based analog phase shifters. Its narrow bandwidth is due to the use of the quarter-wave impedance transformer and this is probably the price to pay for the automatic impedance matching in the band.

Table 1. Performance comparison

Ref.	Frequency (GHz)	BW (%)	Size (λ_0)	Phase shifting range (º)	RL/IL (dB)	Amplitude imbalance (dB)	Control of C_0 and L_0 in Eq. (1)
[1]	0.8	70	0.07×0.27	360 (discrete)	13/2.5	0.6	-
[3]	5.0	26	0.17×0.34	0-125	10/3.6	1.8	C_0 only
[4]	6.5	46	-	0-90	10/3.0	2.5	Separate
[5]	2.4	42	0.28×0.47	−97-100	15/2.0	0.8	Separate
This work	2.4	4	0.17×0.19	−74.2-211	15/1.7	0.4	Simultaneous

BW=bandwidth, RL=return loss, IL=insertion loss.

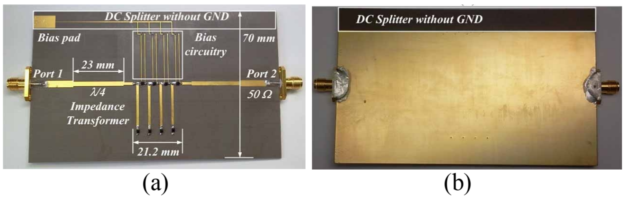


Fig. 3. Photograph of fabricated tunable phase shifter. (a) top view, (b) bottom view.

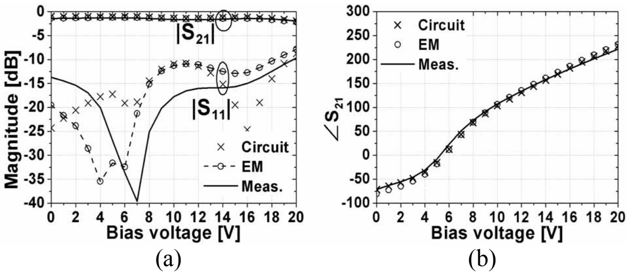


Fig. 4. Circuit-, electromagnetic (EM)-simulated, and measured S-parameters for different bias conditions. (a) $|S_{11}|$ and $|S_{21}|$, (b) $\angle S_{21}$.

Ⅳ. Conclusion

A compact MTM-based tunable phase shifter consisting of four unit cells has been designed at 2.4 GHz. The size of the phase shifter is 0.17 λ_0×0.19 λ_0. The phase of the proposed MTM phase shifter can be controlled conveniently with one voltage source applied in the range of 0 V to 19 V. The measured phase shifting range of the proposed MTM phase shifter is from −74.2° to 211° at 2.4 GHz. The measured insertion loss of the phase shifter is approximately 1.5 dB. The balanced impedance condition of the MTM TL is automatically satisfied over the entire phase shifting range. The insertion loss of the phase shifter may be improved further, depending on the fabrication technology of the chip varactors. This phase shifter can be easily constructed at low cost on any printed circuit board (PCB).

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