QUASI-OPTICAL PHASE MODULATORS

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Abstract— **Three X-band quasi-optical transmission-type phase modulators are presented: a varactor loaded grid with 25° continuous phase shift; a *p-i-n* diode loaded grid with digital phase shifts of 0° and 90°; and a transistor antenna array with 0° and 180° phase states. All of the modulators operate in transmission mode and are suitable for cascading with other quasi-optical components. Relative amplitude and phase change of the transmission coefficient as a function of frequency is presented for the two digital modulators. Antenna patterns for the BPSK active antenna array modulator are also presented.**

I. Introduction

A VARIETY of quasi-optical active components have been demonstrated to date: oscillators [1]; various amplifiers [2], [3]; as well as gratings loaded with diodes for wave switching [4], frequency conversion [5], tuning [6], mixing [7] and reflection beam-steering [8], [9]. The phase shifters consist of arrays of Schottky diodes whose rows are biased independently, thus producing a linearly varying phase shift across the plane of the array of up to 70°. These arrays produce a phase shift in one dimension. Two-dimensional beam-steering was also proposed using two arrays in parallel. Recently, there has been some interest in using active quasi-optical components as front ends in communication systems. For these applications, different types of modulators are necessary. Digital phase modulation is a widely used method in today's communication systems [10], [11], [12]. We have developed two quasi-optical transmission-type digital phase modulators and one analog phase modulator. Two digital modulators can be stacked to form QPSK modulation (0°, 90°, 180° and 270°), whereas the presented varactor grid modulator can be used for phase-error tuning of the previous two.

II. Design

In this section, the design of three types of phase modulators is presented. The measurements are shown in the following section.

(1.) The first approach is an analog phase modulator designed and fabricated as a varactor diode loaded printed grid with a period much smaller than the free space wavelength. The unit cell consists of one varactor diode connected to a vertical line, as can be seen in the array schematic in Fig.1. The diode is biased through the horizontal lines of the 5 × 5 grid. The variable capacitance of the diodes resonates with the inductance of the line, therefore changing the phase of the transmitted wave. Previously reported phase shifters operated in reflection mode, whereas this one operates in transmission mode and is cascadable with other quasi-optical components. However for low transmission loss at least two grids are needed, since large phase shifts are obtained at resonance where the reflection coefficient is high. Metelics MA4ST silicon hyperabrupt tuning varactor diodes are soldered onto a grid with a period of 6 mm printed on a Duroid substrate of ϵ_r = 2.2. A zero-order design

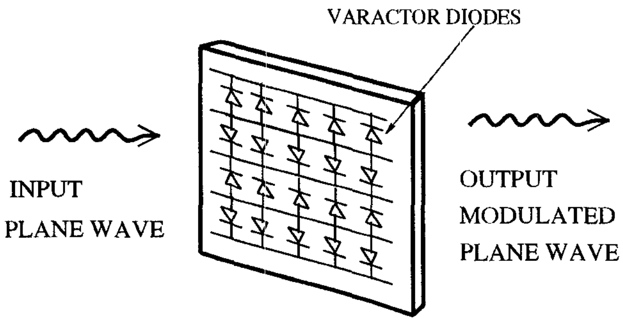

Fig. 1. Varactor diode analog grid modulator.

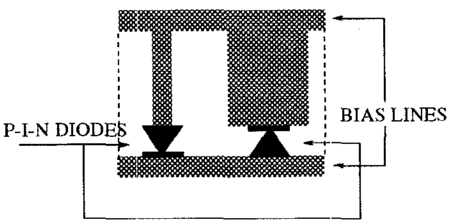

Fig. 2. Quasi-optical transmission-type BPSK grid modulator.

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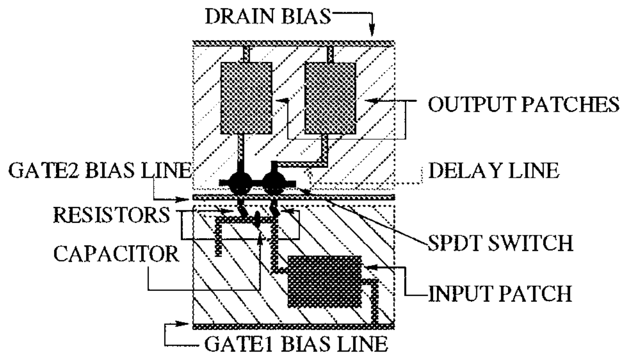

Fig. 3. Unit cell of the BPSK transmission-type active antenna array modulator.

was performed by using a transmission-line model with a diode equivalent circuit given in the Metelics catalog and a grid quasi-static inductance as in [8]. Free space is simulated by a 377-Ω line. A continuous phase shift of about 30° at 5 GHz was predicted from two cascaded grids with an associated transmission coefficient of 1 dB.

(2.) The second approach we have investigated is a printed 10 × 10 grid, with a period much smaller than the free-space wavelength, and loaded with *p-i-n* diodes. Each unit cell of the grid contains two diodes, oppositely oriented with respect to the horizontal bias lines, Fig.2. The diodes are connected to vertical lines of different widths, which represent different reactive loading to an incoming vertically polarized plane wave. When one of the diodes is forward-biased and the other one is reverse-biased, the phase change of the wave transmitted through the grid is much smaller than when the diodes are oppositely biased. Away from resonance, when the transmission loss of a single grid is low, the phase change is also small, so a single grid is not useful for a digital quadrature phase modulator, where 90° phase steps are required. In order to achieve low transmission loss with simultaneous large phase variation between the two states, we use a cascade of two grids. Effectively, this achieves impedance matching to the incoming plane wave. Two grids with unit cells as shown in Fig.2 have been fabricated with a period of 10 mm, and were populated with HP HSMP-3892 surface mount *p-i-n* diodes. A full-wave analysis program MPORT was used for the design [13].

(3.) The third approach is to use active antenna arrays. The unit cell of a 4-element array is shown in Fig.3. The input signal is received by patch antennas and coupled to a PHEMT SPDT active switch circuit, shown in Fig.4. We opted for a switch with gain in order to overcome transmission loss due to antenna mismatch. The outputs of the switch are connected to two output patch antennas with feed lines which are designed to have a length difference of 180 electrical degrees at 10 GHz. PHEMT ATF-35576 transistors are used in the SPDT switches, which are designed with two transistors in parallel, so that when one transistor is biased in pinched-off mode the other is biased as an amplifier. The transistors in the switch are DC isolated by a capacitor. The amplifiers are designed to be unconditionally stable, with resistors placed in the gates for stability. To simulate the switch, the pinch-off S-parameters of the transistor were measured in a 50-Ω environment. A unit cell was simulated using Hewlett Packard's MDS microwave circuit simulator with the measured S-parameters.

III. Measurements

An HP8510 network analyzer was used for the grid modulator measurements. The grids were placed in the far field of the transmitting and receiving horn antennas connected to the two ports of the network analyzer. An absorbing sheet was placed around the grid to minimize diffraction. A response calibration was performed with-

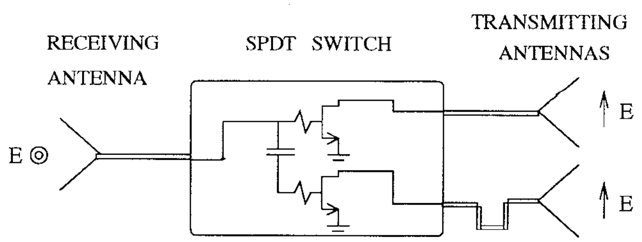

Fig. 4. Schematic of the unit cell of the active array BPSK modulator.

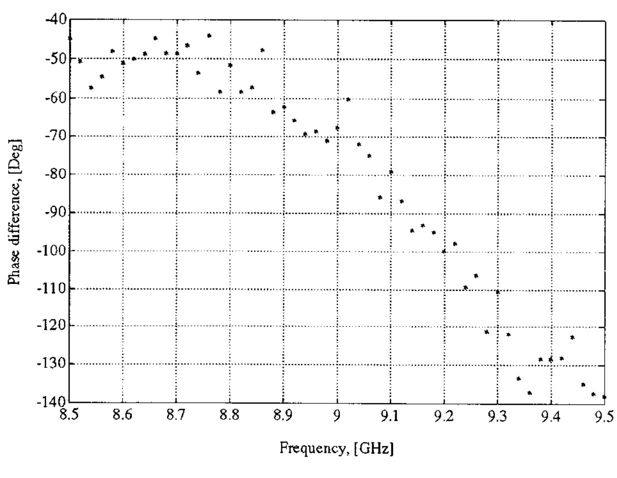

Fig. 5. Phase shift for the BPSK quasi-optical transmission-type grid modulator vs. frequency.

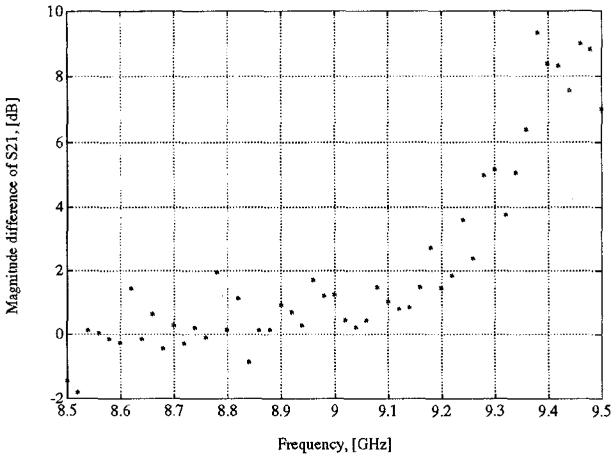

Fig. 6. Relative amplitude for the BPSK quasi-optical transmission-type grid modulator vs. frequency.

out the grid and with the absorbing aperture in place. This sets the reference plane at the surface of the grid.

Two varactor grids were stacked and measured in the setup explained. A continuous, analog phase shift of 25° was measured at 8.5 GHz with about 3 dB of transmission loss. As mentioned before, the transmission-line model predicted 30° of phase shift at 5 GHz. We believe that the difference between the measured and simulated data is due to mismatch between the given low-frequency diode variable capacitance and the actual capacitance at X-band.

For the digital diode modulator with a unit cell as shown in Fig.2, the phase of the transmission coefficient was measured for the two bias states. The grids exhibit a slightly lower operating frequency than designed, probably due to underestimated diode package inductance in the model obtained from the manufacturer. This also resulted in relatively high transmission loss of about 5 dB, while the simulations predicted less than 1 dB at 10 GHz. At 9.1 GHz, a 90° relative phase shift was measured with less than 1 dB of relative amplitude change between the two phase states. Four such modulators can be cascaded for QPSK modulation. The bandwidth is shown to be around 5 %, as shown in the measured data in Fig.5, Fig.6.

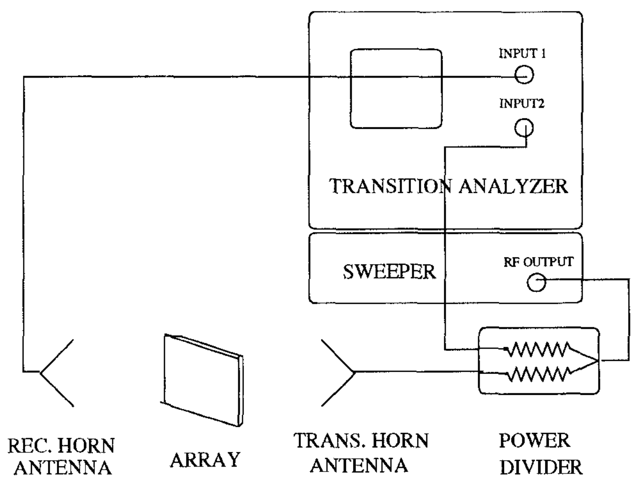

Fig. 7. Experiment setup for the measurement of the BPSK quasi-optical transmission-type active antenna array modulator.

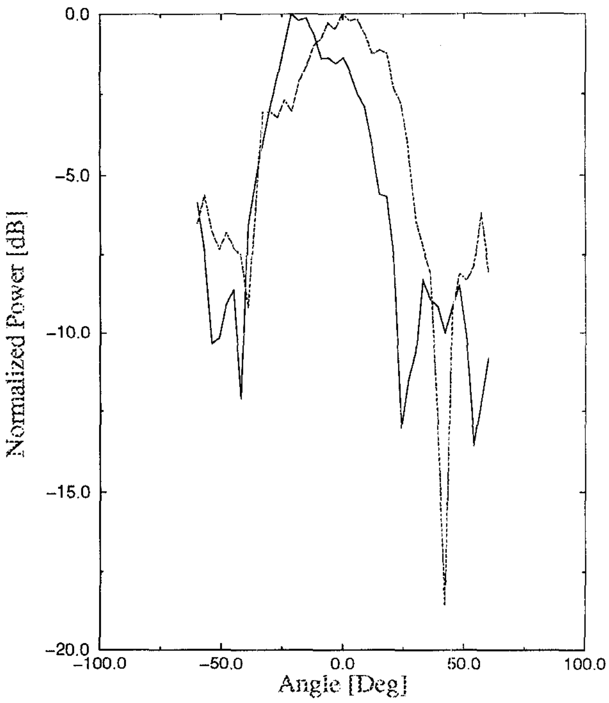

Fig. 8. Far-field pattern measurements of the BPSK quasi-optical transmission-type active antenna array modulator. E-plane dotted line, H-plane solid line.

In the active antenna array modulator measurements, the HP70820A transition analyzer was used, and the measurement setup is shown in Fig.7. The calibration was performed for one state of the amplifier switch from Fig.7, and then the relative phase and amplitude for the other switch state was measured.

The measured relative phase and amplitude from the array are presented in Table 1, from 10.1 GHz to 10.3 GHz. The bandwidth of this modulator is only a few percent, due to the narrow-band nature of the patches. The measured far-field pattern for one position of the switch is shown in Fig.8. The modulation speed of the modulator is low because all of the devices

Frequency, GHz	ΔAmplitude, dB	ΔPhase, deg.
10.1	3.5	174
10.15	2.5	155
10.2	4.2	166
10.25	3.6	172
10.3	2.4	150

TABLE I

MEASURED RELATIVE AMPLITUDE AND PHASE OF THE ANTENNA ARRAY MODULATOR.

are biased in parallel, which results in a large time constant of the switching network.

IV. Conclusion

In summary, we have demonstrated several types of quasi-optical digital phase modulators. We used either diode-loaded gratings, or antenna arrays loaded with transistor SPDT switches. We have demonstrated 90° and 180° electronically variable relative phase shift of a wave in transmission.

V. Acknowledgment

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References

[1] Z. B. Popović, R. M. Weikle II, M. Kim, and D.B. Rutledge, "A 100-MESFET planar grid oscillator" *IEEE Trans. Microwave Theory Tech.*, vol. 39, no. 2, Feb. 1991.

[2] M. Kim, J. J. Rosenberg, R. P. Smith, R. M. Weikle, J. B. Hacker, M. P. DeLisio, and D. B. Rutledge, "A grid amplifier," *IEEE Microwave and Guided Wave Letters*, vol. 1, no. 11, pp. 322–324, Nov. 1991.

[3] J. S. H. Schoenberg and Z. B. Popović, "Planar lens amplifier," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, pp. 429–432, May 1994. San Diego, CA.

[4] K. D. Stephan, F. H. Spooner, and P. F. Goldsmith, "Quasi-optical millimeter-wave hybrid and monolithic pin diode switches," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 1791–1798, 1993.

[5] C. F. Jou et al, " Millimeter-wave diode-grid frequency doubler," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1507–1514, Nov. 1988.

[6] T. Mader, S. Bundy, and Z. B. Popović, "Quasi-optical VCOs," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 1775–1781, Oct. 1993.

[7] J. B. Hacker, R. M. Weikle II, M. Kim, M. P. DeLisio, and D. B. Rutledge. "A 100-element planar Schottky diode grid mixer," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 557–562, Mar. 1992.

[8] W. W. Lam et al., "Millimeter-wave diode phase shifters," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 902–907, 1988.

[9] L. B. Sjogren, H. X. Liu, X. Qin, C. W. Domier, and N.C. Luhmann Jr., "Phased array operation of a diode grid impedance surface," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 565–572, 1994.

[10] Z. B. Popović, J. S. H. Schoenberg, T. Mader, W. A. Shiroma, S. Hollung, M. Marković, J. Dixon, and S. C. Bundy, "Quasi-optical components and subsystems for communications," in *1995 Conf. Proc. of the Int. Symp. on Signals, Systems and Electronics*, San Francisco, CA, pp. 93–98, Oct. 1995.

[11] M. J. Vaughan, W. Wright, and R. C. Compton, "Active antenna elements for millimeter-wave cellular communications," in *1995 Conf. Proc. of the Int. Symp. on Signals, Systems and Electronics*, San Francisco, CA, pp. 9–12, Oct. 1995.

[12] C. W. Pobanz, J. Lin, and T. Itoh, "Active integrated antennas for microwave wireless systems," in *1995 Conf. Proc. of the Int. Symp. on Signals, Systems and Electronics*, San Francisco, CA, pp. 1–4, Oct. 1995.

[13] S. C. Bundy and Z. B. Popović, "A generalized analysis for grid oscillator design," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 2486–2491, Dec. 1994.