A Ka-Band 3-bit RF MEMS True-Time-Delay Network

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***Abstract*—A monolithic Ka-band true-time-delay (TTD) switched-line network containing 12 metal-to-metal contact RF microelectromechanical system switches has been successfully fabricated and characterized on a 75-μm-thick GaAs substrate. The compact 9.1-mm^2 TTD network was designed to produce flat delay time over a dc-to-40-GHz bandwidth with full 360° phase control at 45° intervals at 35 GHz. Measurements show a match to within 2% to the designed delay times at 35 GHz for all eight switch states with 2.2-dB average insertion loss over all states. Peak rms phase error is 2.28° and peak rms amplitude error is 0.28 dB from dc to 40 GHz. Return loss better than 15 dB from dc to 40 GHz for all eight states confirms the circuit's broad-band operation.**

***Index Terms*—Phase shifter, radar antennas, RF microelectromechanical system (MEMS) devices, true-time delay (TTD).**

I. Introduction

THE use of electronically steered arrays is becoming increasingly necessary to meet the performance requirements of modern radar and communication systems [1]. Phase shifters are critical components in such arrays and can often become the performance-limiting component of the system. Traditionally, phase shifters using GaAs transistors configured to switch between different line lengths or filters have been used, but such transistor switches tend to be lossy. Thus, the best pseudomorphic high electron-mobility transistor (pHEMT) 4-bit phase shifter reported to date exhibits an average loss of 6.5 dB at Ka-band [2]. In contrast, recently several RF microelectromechanical system (MEM)-based phase shifters have been reported that exhibit greatly reduced insertion loss [3]–[5]. This paper expands upon these results by demonstrating very low loss and parasitics, but over much larger bandwidths and in a more compact and manufacturable assembly. Furthermore, the monolithic integration of pHEMT monolithic-microwave integrated-circuit (MMIC) devices with the RF MEMS switches used here has already been demonstrated [6]. Consequently, monolithically integrating the phase shifter with Ka-band amplifiers, oscillators, and mixers is a straightforward approach to further reduce overall antenna cost and complexity.

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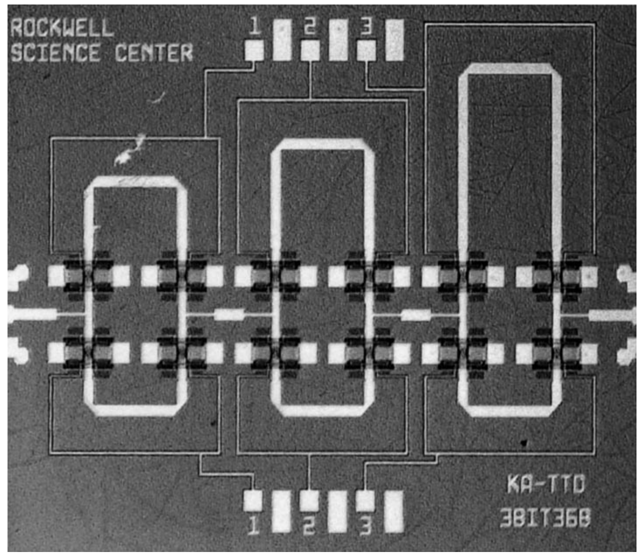

Fig. 1. 3-bit RF MEMS phase shifter. The substrate is 75-μm–thick semi-insulating GaAs with 2.1-μm-thick gold traces. The circuit is 3.5 $\times$ 2.6 mm in size.

II. Circuit Architecture and Design

Past progress on metal-to-metal contact MEMS switches developed at Rockwell Scientific, Thousand Oaks, CA, [7] has enabled monolithic fabrication of high-quality switched-line true-time-delay (TTD) networks. These switches use a movable metal shunting bar to connect two RF signal lines when the dc activation voltage of 75 V is applied. Measurements on discrete Rockwell Scientific switches show a typical dc/RF contact resistance of $2 \times 0.5\ \Omega$, while the off-switch coupling capacitance is only 1.75 fF. Networks constructed with as many as 24 MEM switches with acceptable yield and uniformity are possible given the current level of switch maturity.

The 3-bit phase shifter is of the switched-line type using a network of microstrip lines, 55-μm wide, on a 75-μm-thick GaAs substrate (Fig. 1). Six SPDT tee junctions, each with two MEMS switches, are used to route the signal through the selected microstrip delay path. Consequently, performance is highly dependent upon the design of the tee junction since, for any selected bit state, the signal must traverse six switches and tee junctions.

The tee junctions were optimized to provide the best possible impedance match and delay flatness over the Ka frequency band by adding a series inductance matching circuit in front of each junction. The series inductance compensates for the mismatch that comes from the open-stub transmission line connected to the open switch at each tee junction. Generally,

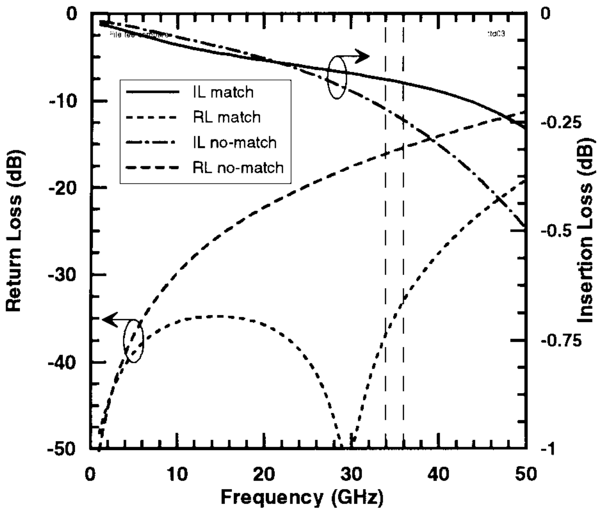

Fig. 2. Method-of-moments (MoM) simulation results for a single SP2T tee junction with and without inductive impedance matching are compared. Above 20 GHz, both the insertion and return losses of the unmatched junction become unacceptable.

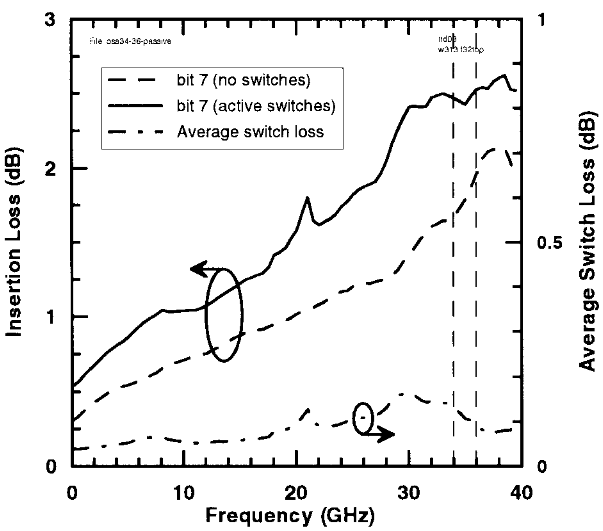

Fig. 3. Measured insertion loss for bit 7 of the active TTD network compared to an equivalent single-bit structure with the switches replaced by fixed metal shorts. The active network insertion loss is 0.6 dB more than the passive structure corresponding to a loss of 0.1 dB per switch at 35 GHz.

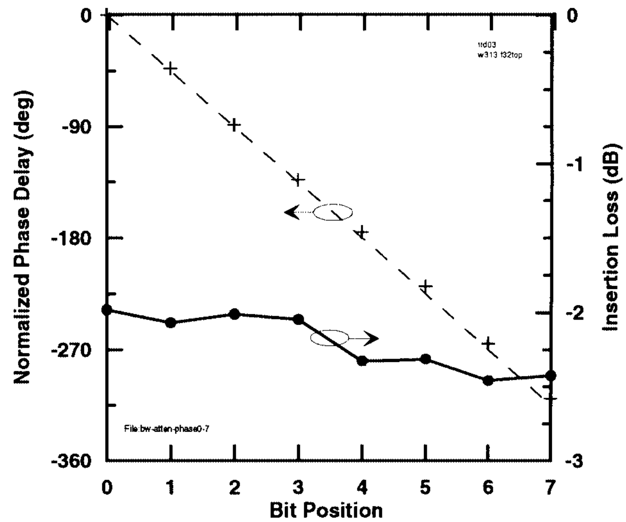

Fig. 4. Measured (+) and simulated (dashed) insertion phase and measured loss (●) of the 3-bit TTD network at 35 GHz.

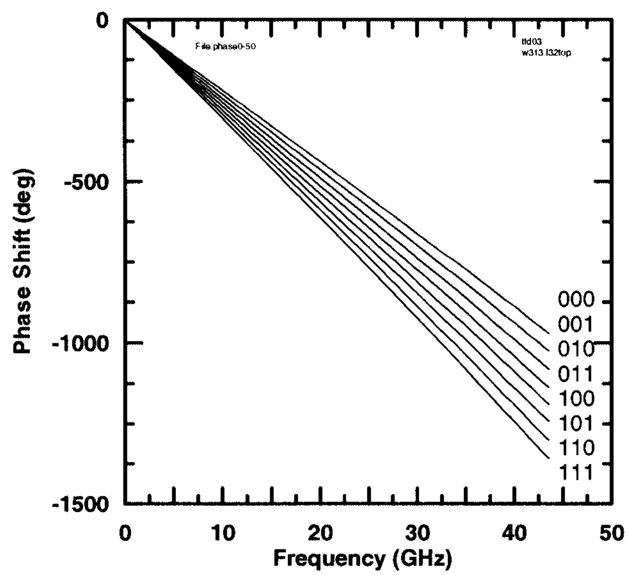

Fig. 5. Measured insertion phase of the 3-bit TTD network for each delay state. The circuit's broad-band performance is clearly evident.

a reactive element degrades the delay flatness when used alone. However, in this case, a proper choice of inductance can reduce the delay ripple caused by the open stub [3]. The phase shifter clearly cannot operate at the frequency where this open stub is a quarter-wavelength and the RF signal is completely reflected at the tee junction. However, even at frequencies well below this limit, the mismatch introduced by the open-stub transmission-line capacitance creates a resonance that results in increased dispersion in the group velocity. Therefore, to allow for the broadest usable frequency range, the open-stub length for the phase shifter is kept as short as possible and the physical switch size ultimately limits how small the stub length can be reduced.

To allow for Ka-band operation, the already compact Rockwell Scientific switch geometry was tightened to the maximum extent possible without compromising switch functionality, thereby resulting in an open-stub length at each tee junction of only 156 μm. This length corresponds to a quarter-wave-length at approximately 158 GHz, thus, the RF signal will be completely reflected at the tee junction at this frequency. Adding an inductive microstrip matching section, 16-μm wide and 150-μm long, in series with the tee junction optimized circuit performance by minimizing circuit mismatch and phase dispersion up to 40 GHz.

Fig. 2 compares the performance of a single tee junction with and without the inductive matching sections. Both matched and unmatched circuits show good return loss at frequencies below 20 GHz. However, above 20 GHz, the return loss for the unmatched tee monotonically degrades to 15 dB through Ka-band, whereas the matched tee shows return loss better than 33 dB. Similarly, the insertion loss nearly doubles to 0.25 dB for the unmatched tee compared to 0.16 dB for the matched tee at 35 GHz.

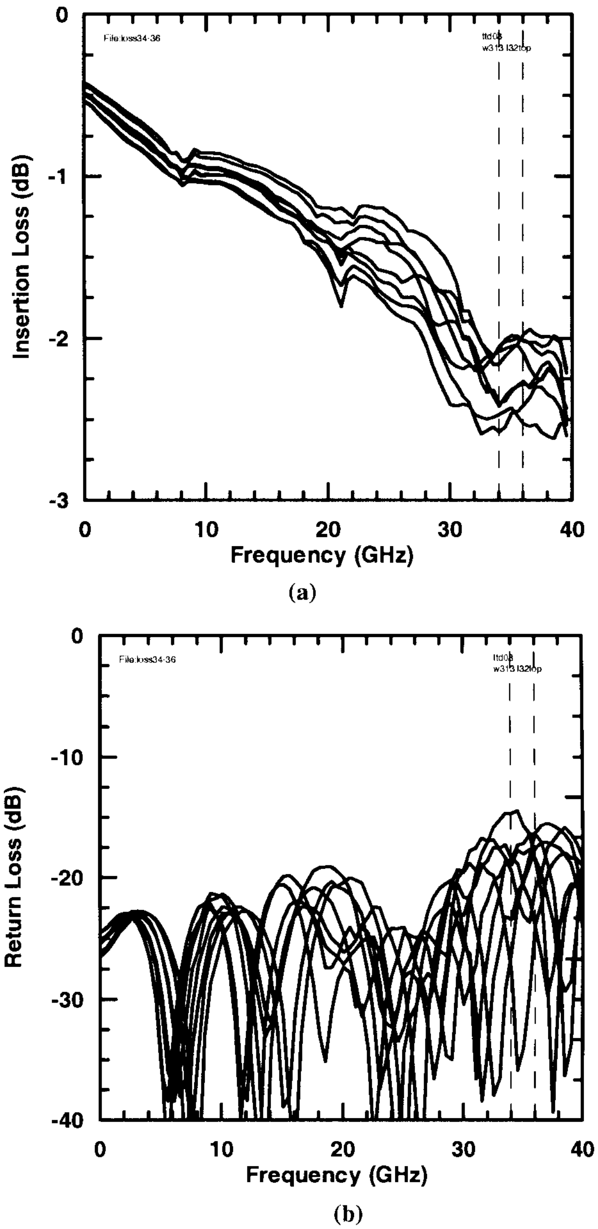

Fig. 6. Measured: (a) insertion loss and (b) return loss for all eight delay states of the phase-shifter network.

III. PHASE-SHIFTER PERFORMANCE

In order to isolate the switch loss from delay-line loss, a passive single-bit structure corresponding to the longest delay path (bit 7) of the active TTD network was fabricated and tested. Fixed metal shorts were used in place of the MEMS switches. This passive circuit showed 1.8 dB of conductor loss at 35 GHz (Fig. 3). This number matches well with the loss predicted by an Agilent Momentum[1] simulation with a metal thickness of 2.1 μm and a conductivity of 4×10^7 S/m. The corresponding insertion loss of the active TTD circuit with MEMS switches set for the same delay was 2.4 dB at 35 GHz, 0.6 dB greater than the passive circuit. Thus, the average switch loss is measured to be 0.1 dB corresponding to $2 \times 0.5\ \Omega$ contact resistance per switch.

[1]*Advanced Design System 2001*, Agilent Technol. Inc., Santa Clara, CA, 2001.

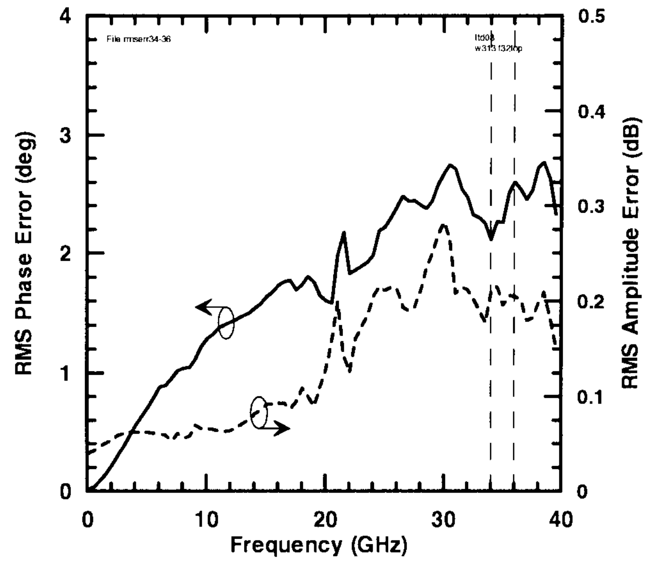

Fig. 7. Measured rms phase and amplitude error of the phase shifter over the full frequency band.

Each of eight different sets of switch positions for the 3-bit TTD network was tested using an on-wafer RF probe station. The monolithic TTD network employing eight MEMS switches (Fig. 1), 3.5×2.6 mm^2 in size, was designed to produce delay times from 61.0 to 86.0 ps at 3.57-ps intervals over a dc-to-40-GHz frequency range. The delay time step corresponds to 45° of phase shift at 35 GHz and is realized with 356-μm-long delay lines. Six separate dc-bias lines, carrying either 0 or 75 V, were used to control the switch positions. Fig. 4 summarizes the measured performance of the 3-bit TTD network. The plot in Fig. 5 shows both linearity and the amount of phase shift achieved from the matched TTD network. The measured phase difference between the shortest and longest paths was 310° at 35 GHz, which is within 1.6% of the desired phase shift of 315°. The variation in insertion loss for all eight states was only 0.48 dB (from 1.98 to 2.46 dB) at 35 GHz [see Figs. 4 and 6(a)]. The return loss was better than 15 dB for all delay states over the Ka frequency band [see Fig. 6(b)].

The difference between group delay times for each bit state matches closely with the designed delay times (Fig. 4). At 35 GHz, the largest deviation from the designed delay times was approximately 5.1° (0.4 ps). The measured insertion loss at 35 GHz for all eight states also matches well with the predicted loss numbers when 0.1-dB-per-switch loss was added to the estimated conductor losses from the delay lines.

The rms average phase and amplitude error has been computed based on the measured data and is plotted in Fig. 7. The rms phase error increase with frequency indicates that the simulated phase velocity of the microstrip lines are slightly offset from the realized value. This error can be compensated for in the future by a slight change in the delay-line lengths. Nevertheless, the peak rms phase error is very low, with a maximum of 2.8° at 38 GHz. Averaged from dc to 40 GHz, the rms phase error is 2.0°. The peak rms amplitude error over frequency is similarly low, with a maximum of 0.28 dB at 30 GHz. Averaged from dc to 40 GHz, the rms amplitude error is 0.16 dB.

IV. Conclusion

A 3-bit TTD networks with direct metal-to-metal contact MEMS switches designed to operate at the Ka-band has been reported. Phase-shifter performance was greatly enhanced by inserting a simple high-impedance matching section. Nearly flat delays up to 40 GHz for all eight switch states were achieved in a compact 9.1-mm^2 circuit.

Acknowledgment

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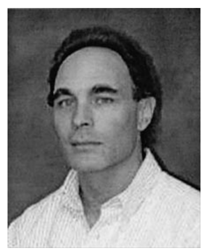

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