Distributed MEMS Transmission-Line BPSK Modulator

N. Scott Barker and Gabriel M. Rebeiz

***Abstract*—The application of a distributed microelectromechanical system (MEMS) transmission line as a binary phase shift keying modulator is presented. This modulator has the advantages of low loss and low required drive power compared to a typical semiconductor-based phase modulator. However, the modulation rate is limited by the mechanical resonant frequency of the MEMS bridges.**

***Index Terms*—Micromechanical devices, millimeter-wave phase shifters, modulators, phase shift keying.**

I. Introduction

THIS letter describes the operation of a distributed microelectromechanical system transmission line (DMTL) as a phase modulator. It has been demonstrated that the DMTL could be used as a phase shifter capable of achieving more phase shift simply by increasing the length of the line. Thus, a micromechanical binary phase shift keying (BPSK) modulator can be designed by using a line with 180° phase shift. The DMTL BPSK modulator requires very little drive power compared to most semiconductor-based phase shifters. However, it is limited in how fast it can modulate due to the mechanical motion of the bridge.

II. Measurements

A DMTL with 96 bridges was designed to give over 180° phase shift at 35 GHz and above [1]. The DMTL is fabricated on a 500-μm quartz substrate with a bridge length $W + 2G$ of 300 μm, as seen in Fig. 1. The measured DMTL has a bridge height g_o of approximately 0.9 μm, a bridge spacing s of 197 μm, a bridge width w of 35 μm, and a coplanar waveguide (CPW) center conductor width W of 100 μm. The measured pulldown voltage V_p for this DMTL is just above 6 V. Figs. 2 and 3 show the S-parameters and phase shift measurements of the DMTL and exhibit an insertion loss of 3.5 dB and a phase shift of 180° at 35 GHz. The DMTL used here is not optimized for lowest insertion loss. Through optimizing the design, it is possible to obtain 1.5–1.8 dB/180° phase shift at 30–60 GHz in a considerably shorter length [2].

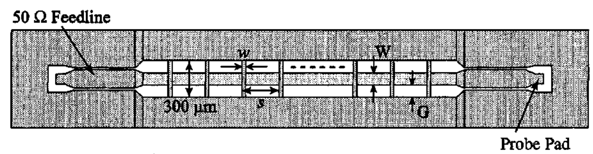

Fig. 1. Layout of a portion of a DMTL constructed of a CPW line with center conductor width W and total CPW width $W + 2G$, and MEMS bridges with width w and spacing s.

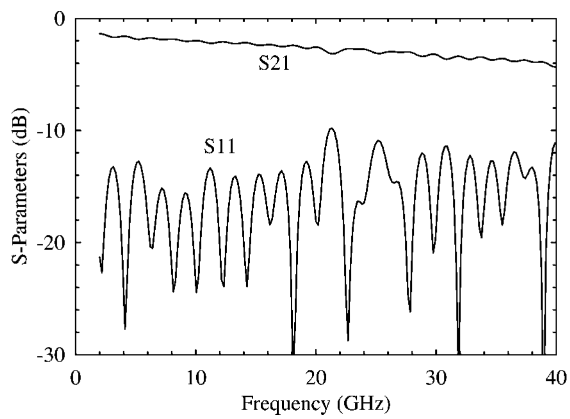

Fig. 2. Measured S-parameters of the 96-bridge DMTL at a maximum bias voltage of 6 V.

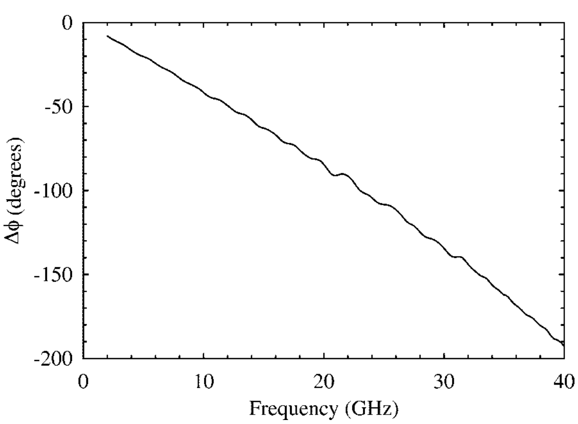

Fig. 3. Measured phase shift of the 96-bridge DMTL at a maximum bias voltage of 6 V.

The DMTL is measured as a BPSK modulator by applying the modulating signal to the center conductor. The signal changes the bridge height, resulting in a 180° phase shift at the output of the DMTL. The modulated RF (35 GHz) at the output of the DMTL is mixed down, using a harmonic mixer, to a frequency range that can be observed with a digital sampling oscilloscope. In this case, the modulating signal is a 0–6 V 1-kHz square wave.

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This signal is coupled to the DMTL center conductor using a bias tee.

It is important to note the use of a back-to-back waveguide-to-coax transition between the bias tee and the RF generator. Although the bias tee will prevent dc from passing through to the frequency generator, it will not completely block the modulation signal from reaching the RF source. The 1-kHz modulation signal could cause unwanted modulation and harmonics in the 35-GHz source. With the back-to-back transition in place, the modulation signal is far below cutoff (31.36 GHz for WR-19), and thus is not able to reach the RF source. The RF is set to 35 GHz, and the intermediate frequency (IF) is chosen to be 10 kHz. Thus, the local oscillator signal to the harmonic mixer is set to 17.5 GHz minus 5 kHz.

The measured IF signal is shown in Fig. 4, and the phase changes can be seen at 0.37 and 0.87 ms. Since the modulating signal is a 1-kHz square wave, phase *changes* occur at twice that rate, or every 0.5 ms. The change in amplitude for the different phase states is relatively small since S_{21} of the DMTL changes by only ~0.5 dB for 0 and 6 V at 35 GHz.

The RF spectrum of the modulated signal, shown in Fig. 5, is measured by taking the output of the DMTL through another back-to-back waveguide-to-coax transition and into a spectrum analyzer. The carrier at the output of the DMTL, with no modulation, was measured to be −14.7 dBm. As can be seen from the measured spectrum, the carrier is suppressed by 25 dB as expected for a BPSK spectrum. The measured power levels of the modulation spectrum, in dB below the carrier (dBc), are shown in Table I.

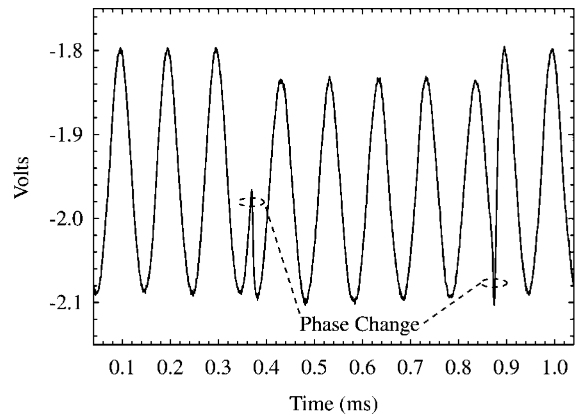

Fig. 4. Measured output of the DMTL as a BPSK modulator with a modulation rate of 1 kHz. The RF is at 35 GHz and is mixed down to 10 kHz as shown here. Phase changes can be observed at 0.37 and 0.87 μs.

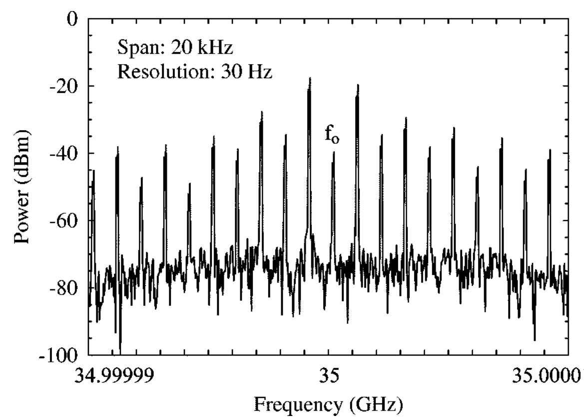

Fig. 5. Measured RF spectrum of the DMTL as a BPSK modulator with a modulation rate of 1 kHz. The carrier, with no modulation, was measured to be −14.7 dBm.

III. MODELING

The theoretical spectrum of a phase-modulated signal can be broken into Fourier components, assuming a periodic modulation signal, given by [3]

$$c_n = f_m \int_0^{T_m} e^{jm_p(t) - jn\omega_m t}\, dt \tag{1}$$

where f_m is the modulation rate, $T_m = 1/f_m$, n is the harmonic number, and $m_p(t)$ is the modulation signal. BPSK modulation is phase modulation with a square wave signal and a phase deviation of 180°. Evaluating (1) under these conditions, the theoretical spectrum of a BPSK signal is found. The calculated theoretical values, given in Table I, are seen to agree reasonably well with the measured values.

The differential equation of motion for the MEMS bridge is given by

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = -\frac{1}{2}\,\frac{\epsilon_o W w V^2}{(g_o - x)^2} \tag{2}$$

where m is the mass of the bridge, b is the damping coefficient, k is the spring constant, g_o is the bridge height, w is the bridge width, W is the width of the CPW center conductor, x is the position of the bridge away from g_o, and V is the applied dc voltage. Using this equation, a numerical solution for the bridge movement with time is found and plotted in Fig. 6. The parameters of the bridge used in this calculation are given in Table II, where t_b is the bridge thickness and the spring constant k is 5.0 N/m, which takes into account the small compressive stress within the bridge. The pulldown voltage is given by $V_p = \sqrt{(8kg_o^3)/(27\epsilon_o \mathrm{W}w)}$ and the damping coefficient is given by $b = k/(Q\omega_o)$, where the resonant frequency is $\omega_o = \sqrt{k/m}$. It is assumed that the quality factor Q in these beams is dominated by squeeze-film damping [4].

The solution for the bridge height versus time can be used to determine the capacitance of the bridge, which in turn is used to determine the insertion phase of the DMTL versus time. This phase is the modulation signal $m_p(t)$ and is used in (1). As can be seen in Fig. 6, the rise time of the bridge is faster than the fall time due to the difference between the electrostatic force pulling the beam down and the restoring force pulling the beam back up. This is the source of the small difference in the magnitudes between the upper and lower sidebands of the measured spectrum (Table I). The calculated sidebands from the numerical model are shown in Table I and agree very well with the measured values. It is seen that the numerical model predicts the amplitude imbalance in the upper and lower sidebands and the 25-dB suppression of the carrier.

The average drive power required by the DMTL can be found from determining the total energy required to move the bridges

TABLE I
MEASURED, THEORETICAL, AND MODELED RF SPECTRUM OF THE BPSK SIGNAL IN dBc

Harmonic	f_{-9}	f_{-7}	f_{-5}	f_{-3}	f_{-1}	f_0	f_1	f_3	f_5	f_7	f_9
Theoretical (dBc)	-23	-20.8	-17.9	-13.5	-3.9	$-\infty$	-3.9	-13.5	-17.9	-20.8	-23
Modeled (dBc)	-27.4	-23.4	-18.8	-13	-3.1	-26	-5.1	-15.1	-19.4	-22.1	-24.2
Measured (dBc)	-23.5	-22.8	-20.3	-13	-3	-25	-5	-14.8	-17.8	-20.8	-24.3

TABLE II
PARAMETERS OF THE GOLD BRIDGE USED IN THE CALCULATION OF FIG. 6

w	35 μm	W	100 μm
l	300 μm	Q	0.55
t_b	2.2 μm	f_o	16.8 kHz
g_o	0.9 μm	V_p	6.1 V

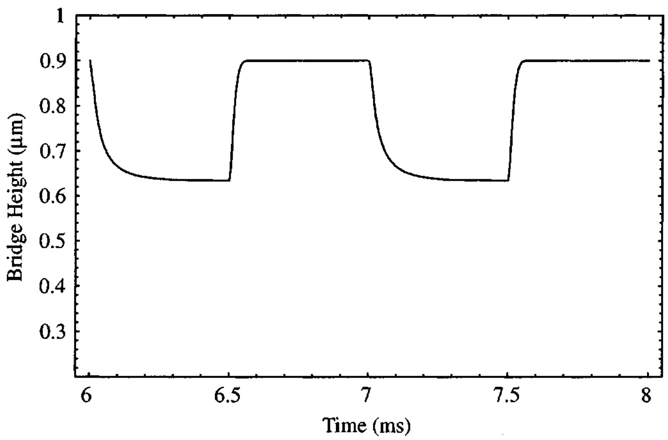

Fig. 6. Numerical simulation of bridge movement under 6-V 1-kHz square wave modulation.

and charge the capacitance multiplied by the frequency of modulation. The energy required to charge the capacitance of the line and bridges is given by

$$U_C = \tfrac{1}{2} C_{\rm tot} V^2 \tag{3}$$

where $C_{\rm tot}$ includes the bridge capacitance in the down state $C_{\rm bd}$, as well as the transmission-line capacitance C_t, and is given by $C_{\rm tot} \approx n \cdot C_{\rm bd} + n \cdot s \cdot C_t$, where n is the total number of bridges on the DMTL and s is the spacing of the bridges. The energy required to move one bridge is found by integrating the electrostatic force over the distance moved

$$U_b = \int_{2g_o/3}^{g_o} \frac{\epsilon_o \mathrm{W} w V^2}{2g^2}\, dg = \frac{\epsilon_o \mathrm{W} w V^2}{4g_o} = \frac{1}{4} C_{\rm bo} V^2 \tag{4}$$

where the maximum possible distance has been used to provide an upper bound on the energy. The energy dissipated through damping has been neglected in this case due to its relatively small contribution to the total energy. The total required power is given by

$$P = nfV^2\left(\tfrac{1}{4} C_{\rm bo} + \tfrac{1}{2} C_{\rm bd} + sC_t\right) \tag{5}$$

where f is the frequency of modulation.

For the 96–bridge DMTL with a bridge height of 0.9 μm and a transmission-line impedance of 96 Ω ($\epsilon_r = 3.78$), the zero bias bridge capacitance is approximately 47 fF and the down state bridge capacitance is taken to be 56 fF. The total capacitance to be charged is 6.4 pF, and the total energy required is 0.156 nJ. With a 1-kHz modulation rate, this results in an average drive power of ~0.16 μW, which is extremely low.

This design is limited to 5-kHz operation due to the low resonant frequency of the bridge. However, our calculations show it is possible to design MEMS bridges with resonant frequencies as high as 200 kHz by reducing the length of the bridge [5]. This results in a larger spring constant and therefore a higher pulldown voltage of 25–40 V. For such a design operated at 10 kHz (20 kbs), the average drive power increases to 20–40 μW. This is still much lower than semiconductor-based modulators, which are typically on the order of a few milliwatts or more [6].

IV. CONCLUSION

We have demonstrated the application of a distributed MEMS transmission line as a BPSK modulator. The DMTL modulator requires much lower drive power and exhibits lower insertion loss than a typical semiconductor-based modulator. However, the modulation rate is limited by the mechanical resonant frequency of the MEMS bridges.

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