Waveguide-Mounted RF MEMS for Tunable W-band Analog Type Phase Shifter

D. PSYCHOGIOU[1], J. HESSELBARTH[1],
Y. LI[2], S. KÜHNE[2], C. HIEROLD[2]

[1]Laboratory for Electromagnetic Fields and Microwave Electronics (IFH)
[2]Group of Micro and Nanosystems (MNS) Swiss Federal Institute of Technology Zurich (ETH), 8092 Zurich, Switzerland

Abstract. A novel MEMS enabled W-band waveguide transmission phase shifter is presented. It consists of a ridge waveguide half-wavelength long resonator and an electrostatically actuated tilting micro-mirror MEMS. Operation is described as a distributed variable shunt capacitance realized by rotating, anti-parallel oriented MEMS conductive fingers. A deflection of the fingers of 0º…7.5º results in a phase shift variation of 0º…35 at 102GHz with an insertion loss of less than 0.73 dB.

1. Introduction

The specific properties of millimeter-waves enable the development of high-capacity communication links, high resolution imaging, radar and sensing systems. Millimeter-wave phase shifters are fundamental components of phased arrays and beam steering systems used in such applications.

W-band (frequency 75 GHz…110 GHz) phase shifters presented in the literature are typically based on switched transmission lines or variable capacitive loads using RF MEMS [1, 2]. Alternatively, the material properties of ferroelectrics and ferrites are tuned by external E-field or H-field, resulting in a phase shifting operation [3]. The first approach is limited by low power handling capability, high dissipation loss and discrete phase shift. In the second approach, continuous phase shift is feasible but leads to bulky structures and increased dissipated power due to the large dielectric loss of the materials.

Mounting the MEMS inside an air filled metal waveguide has the potential to overcome the obstacles mentioned above [4]. The waveguide-MEMS concept was first introduced in [5, 6] for the application of waveguide switches at frequencies up to 16 GHz.

A subsequent development showed a reflection-type W-band phase shifter based on a MEMS-tunable reflector using the high-impedance surface (HIS) concept [7]. When expressing phase shifter performance in terms of a figure of merit (FOM) defined by the ratio of maximum relative phase shift to the maximum insertion loss (degrees per dB), the HIS-based reflection phase shifter achieves a FOM of 68º/dB (based on simulated data given in [7]).

In this paper, we present a novel MEMS enabled W-band transmission phase shifter. The proposed device consists of a ridge waveguide resonator and an electrostatic actuated tilting micro-mirror MEMS as a tuning element placed beneath the ridge. Then, variation of transmission phase is achieved by means of a variable distributed capacitive loading of this resonant ridge waveguide section. The packaging concept proposes a multilayer circuit board (*e.g.*, LTCC) to accommodate the MEMS, covered a by three-dimensional ridge waveguide structure which can be produced by conventional and electron-discharge machining techniques.

2. Phase Shifter Concept

The variation of transmission phase by means of a variable shunt capacitor is limited by the effect of increased input reflection. For example, a shunt capacitor C in a transmission line environment of characteristic impedance Z (see Fig. 1a) and operating at frequency f, shows an input reflection S_{11} and transmission S_{21} of respectively:

$$S_{11} = \frac{-y}{2+y}, \quad S_{21} = \frac{2}{2+y}, \quad y = 2j\pi f CZ \qquad (1)$$

From eq. (1), there is zero mismatch for C=0, whereas a larger C results in mismatch and increased transmission phase. Assuming a worst-case input reflection of –15 dB (corresponding to a worst-case insertion loss of –0.14 dB), the maximum achievable phase shift (that is, variation of transmission phase) is about 10.2º.

Phase shift can be increased at the cost of reduced frequency bandwidth, by placing the variable capacitor in a resonator. Then, the worst-case input reflection (and insertion loss) may occur at both the minimum and the maximum capacitance settings. For example, a half-wavelength transmission line resonator of characteristic impedance $Z_R \neq Z$, with a centered variable shunt capacitance, can be used as a transmission phase shifter. Example structures shown in Fig. 1b and Fig. 1c both realize about twice the maximum achievable phase shift, compared to the structure of Fig. 1a.

More complicated structures comprising variable shunt capacitors and transmission line sections can be envisaged. The structure shown in Fig. 1d, comprising of three variable shunt capacitors separated by two identical short transmission line sections, can realize a large maximum achievable phase shift. Assuming the center capacitance equaling n = 3.5 times one end-capacitance, the maximum achievable phase shift in transmission (for worst-case input reflection of −15 dB) is about 128º.

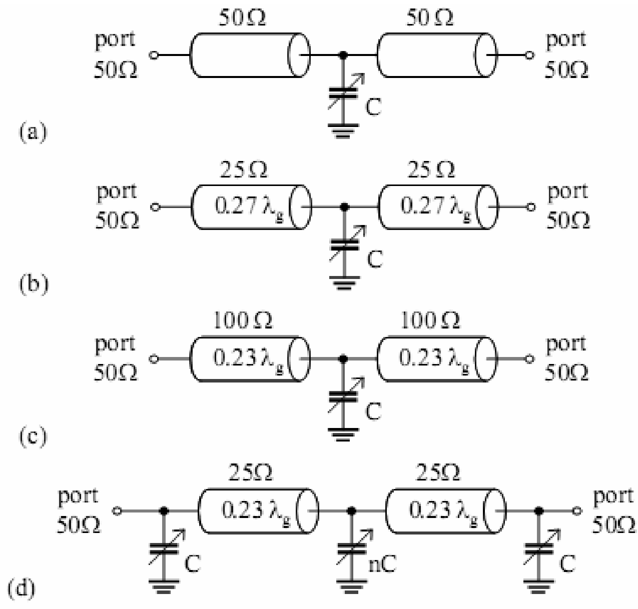

Fig. 1. Phase shifter equivalent circuits. For identical conditions (S11 below −15dB, S_{21} better than – 0.14dB), circuit (a) gives a transmission phase variation of about 10º, (b) and (c) each give about 20º, and (d) gives about 128º with n = 3.5.

Note that there is a tremendous increase of the transmission phase shift range between the structures of Fig. 1a,b,c and the one of Fig. 1d. The idea of the proposed waveguide-MEMS phase shifter is to approximate a structure shown in Fig. 1d using a single MEMS. The actuated part of this MEMS shall be large (that is, not small compared to the wavelength) such that its spatially distributed influence on the electromagnetic fields can indeed be approximated by the circuit of Fig. 1d.

The proposed MEMS chip is placed beneath the waveguide ridge as shown in Fig. 2. It consists of two sets of conductive fingers which are either set flat in the waveguide bottom wall, or rotate in an anti-parallel fashion out of the bottom wall plane and towards the ridge. By doing so, the distance between the respective ends of the fingers and the low-impedance ridge varies, forming the two outer variable capacitors of Fig. 1d. The part in the center of the fingers also moves with respect to the central part of the low-impedance ridge, thereby approximating the middle variable capacitor of the equivalent circuit of Fig. 1.

The length of a finger (and also the length of the low-impedance ridge section) is approximately slightly less than half a wavelength, thereby approximating the transmission line sections of the equivalent circuit of Fig. 1d.

The ridge waveguide is proposed to be formed from a three-dimensional machined part connected to the flat metalized surface of a circuit board (*e.g.*, LTCC). The MEMS chip is then placed in an open cavity of the circuit board. The connection between board and waveguide is helped by alignment pins and uses conductive glue. Bias wiring is embedded in the circuit board. Fig. 3 highlights this assembly concept.

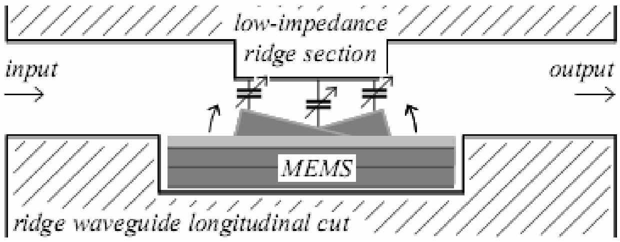

Fig. 2. Waveguide-MEMS phase shifter concept. Beneath a low-impedance ridge section of length of somewhat less than half a guided wavelength, two sets of conductive fingers rotate upwards in an anti-parallel fashion.Fig. 3.

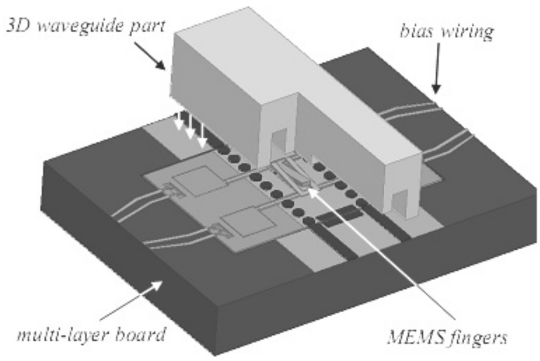

Fig. 3. Waveguide-MEMS assembly concept. The MEMS is located in an open cavity of a multi-layer circuit board. The machined waveguide part comes on top.

3. MEMS Design

RF-MEMS chip design is based on an electrostatic actuated tilting micro-mirror. In [8], the feasibility of an RF variable ratio power divider tuned by a double-side tilting micro mirror is shown. Here, a MEMS design based on bulk silicon micromachining and electrostatic actuation mechanism for a torsional mode of movement is proposed (Fig. 4). High aspect-ratio vertical comb drives and a polymeric SU8 spring allow for large static deflection (0º…7.5º) at low actuation voltage (30 V). A stack of 3 double side polished mono-crystalline Silicon (100) wafers (starting from top: device layer thickness 100 μm, stator layer 180 μm, handle layer 400 μm) and top and intermediate metallization layers are fabricated in a 5 mask process [8]. Specific features improve the RF performance and the phase shifter FOM:

- Geometry: two single-side micro-mirrors arranged in an interdigitated anti-parallel fashion. Such a configuration approximates a multiple-capacitor-loaded resonator. A large beam length keeps the micro-mirrors apart from the comb drive actuators. Accordingly, the chip size is 4 mm × 8 mm.
- Materials: highly conductivity Si is used (σ~75'000 S/m) so as to prevent excessive insertion loss due to E-field penetration into the chip. Low conductivity Si would allow the appearance of RF cavity resonances inside the MEMS chip, which would in turn increase dissipative RF loss.
- Functionality: single-side torsional actuation with a maximum tilt angle of 7.5º at 30 V.

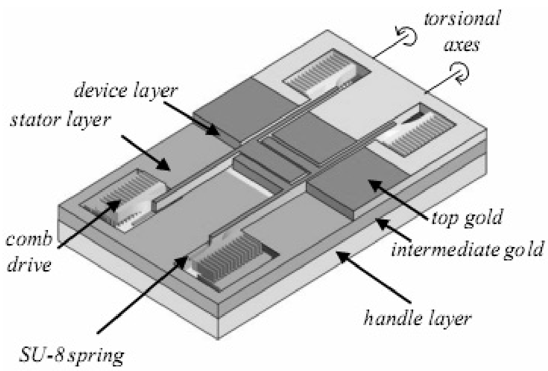

Fig. 4. Dual-axis tilting micro-mirror MEMS schematic.

4. Results and Discussion

The device was simulated using a finite element solver, Ansoft HFSS V13, taking into account all geometrical and material parameters. The simulation results are shown in Fig. 5. At 102 GHz, the maximum transmission phase shift is 35.5^0 with a maximum insertion loss of 0.73 dB.

The phase shift obtained is much smaller than the one obtained from the (idealized) equivalent circuit of Fig. 1d. It is, nevertheless, almost twice as large as expected from a lumped shunt capacitor equivalent circuit, such as shown in

Fig. 1b. This clearly shows that the distributed nature of the interaction of MEMS and electromagnetic field results in an increased performance.

Simulation of the different loss contributions show that more than half of the loss originates from the MEMS silicon. The use of higher conductivity silicon would reduce the loss and increase the FOM. Another significant loss contribution comes from electromagnetic energy channeling through the beam openings in the waveguide wall.

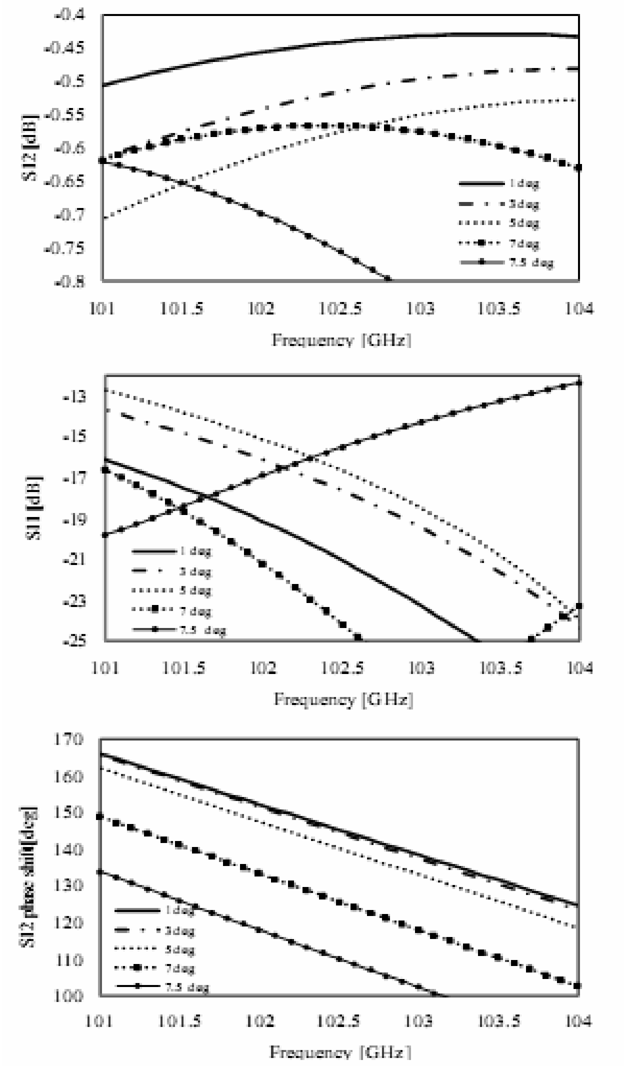

Fig. 5. Simulated phase shifter performance. At 102 GHz, input match is below –15 dB, transmission is above–0.73 dB, and the transmission phase variation is about 35.5º, resulting in a FOM of about 49º/dB.

5. Conclusion

A novel waveguide-MEMS transmission phase shifter is proposed. A tilting micro-mirror MEMS device with anti-parallel fingers realizes a variable distributed capacitive load to a ridge waveguide resonator. For a deflection angle varying between 0º and 7.5º, a transmission phase variation of 35.5º is obtained at an insertion loss of less than 0.73 dB at a frequency of 102 GHz, corresponding to a FOM of 49º/dB. A packaging concept based on a single metal 3D machined part placed on top of a structured multi-layer circuit board is proposed.

Acknowledgement–This work was supported in part by the Swiss National Science Foundation (SNF) under Grant 200021_129832.

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