A Q-Band RF-MEMS Tapered True Time Delay Line for Fusion Plasma Diagnostics Systems

Danqing Fu, Yusha A. Bey, Calvin Domier, Neville C. Luhmann, Jr., Xiaoguang "Leo" Liu
School of Electrical and Computer Engineering, University of California Davis
Email: lxgliu@ucdavis.edu

***Abstract*—In this work, we present the design and demonstration of a novel MEMS-based true-time delay (TTD) unit for microwave imaging reflectometry (MIR) diagnostics of thermonuclear fusion plasmas. The TTD unit is designed using a coplanar waveguide loaded with extended tuning range cantilever-type varactors. The capacitance value of the varactors are tapered at the input and output ports, allowing for better impedance matching in the highly loaded case. More than 360° and 600° phaseshift was demonstrated at 30 GHz and 50 GHz, respectively with a figure of merit better than 60°/dB over the entire frequency range. As a TTD unit, the device can provide near constant delay of 0–33 ps adjustable in an analog fashion. To the authors' knowledge, this is the best TTD unit demonstrated to date in terms of maximum adjustable delay range and FoM in Q-band.**

***Index Terms*—phaseshifters, true time delay, rf-mems.**

I. Introduction & Background

The global climate change crisis has motivated interest in developing long term, non-fossil fuel technologies with magnetic fusion plasma energy offering a clean and virtually inexhaustible approach. However, the problem of anomalous transport in magnetized plasmas and its relationship to small amplitude microturbulence is of critical importance to the eventual realization of magnetic fusion energy. The key to this understanding of the associated electron density fluctuations is microwave reflectometry which is an active, radar-like diagnostic technique. Besides its high sensitivity to density fluctuations, reflectometry provides a localized measurement, relying on the reflection of a microwave beam from the cutoff surface, an opaque layer in the plasma where the index of refraction goes to zero at the probing frequency. When properly coupled, the reflected beam is phase-modulated by fluctuations of the index of refraction near the cutoff surface making it possible to provide an image of the turbulent fluctuations. However, in the presence of 2D fluctuations (i.e. where there are fluctuations in both the poloidal and radial directions), it is difficult to obtain a clear interpretation for the reflectometry data. The difficulty arises from the fact that when the plasma permittivity fluctuates perpendicular to the direction of propagation of the probing wave, the spectral components of the reflected field scatter into a large, solid angle resulting in fragmented wavefronts with a complicated pattern of amplitude and phase fluctuations. The solution is to employ imaging techniques [1] whereby the output of the illumination source is transformed into an extended beam whose curved wave front is designed to roughly match the poloidal shape of the plasma cutoff layer. The wave front curvature matching projects a nearly constant phase front onto the fluctuating layer. The reflected beam passes through additional optics utilized to image the reflecting layer onto the detector array. With such a system, the signal at the detector is purely phase modulated. These microwave imaging reflectometry (MIR) instruments permit one to obtain spatially resolved pictures of the fusion plasma density fluctuations and have been implemented on major fusion devices such as the DIII-D tokamak in San Diego [2] where the system has 4 independent illumination frequencies resulting in 12x4 pixel images (to be expanded to 12x16).

In existing MIR systems, large aperture dielectrics lenses are actuated by electric servo motors to focus the probing beam. Such systems have demonstrated excellent results in imaging the local density fluctuations. However, when certain global parameters of the plasma change, these lens-based systems are too slow to respond on the required timescale.

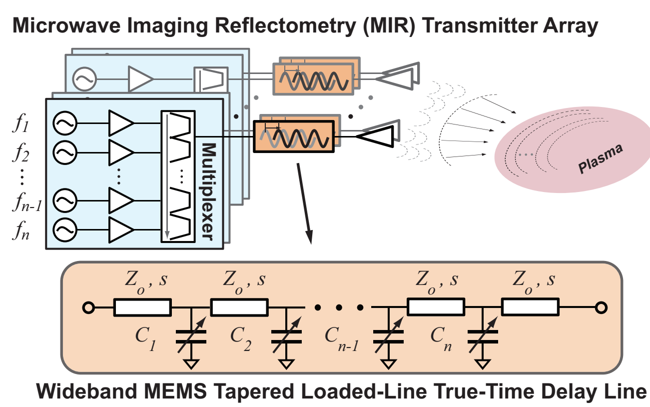

Fig. 1. Concept of a phased-array based MIR transmitter architecture electronic true-time delay units for beam focusing.

One solution to this problem is to use an electronic focusing/de-focusing system. Fig. 1 illustrates a possible transmitter architecture for such a system. The focusing lens is replaced by a phased-array system that uses phaseshifters to provide the desired delay to form a curved wavefront. Several frequencies are used simultaneously to provide the depth information.

The proposed system architecture imposes unique requirements for the phaseshifter elements:

1) The phaseshifter needs to be wideband enough to cover a large depth and cater to a variety of tokamak systems.

For example, 30–50 GHz bandwidth is needed for MIR systems on the National Spherical Torus Upgrade Experiment (NSTX-U) [3] as well as for studies of the important edge pedestal region in the EAST superconducting tokamak [4].

2) A linear phase shift vs. frequency relationship is needed so that different frequencies can be formed onto cut-off surfaces of similar curvatures. In other words, a true-time-delay unit is needed.
3) Large phase shift/delay is required to form the desired curved wavefront.
4) Phase/delay adjustment needs to be of high resolution in order to accurately control the wavefront shape.
5) Because several frequencies are transmitted simultaneously, the phase-shifter needs to be extremely linear.
6) Tuning speed should exceed the plasma fluctuation time-constant (∼ms).

RF-MEMS varactor-loaded TTD lines stand out as a promising candidate that may satisfy all the above design requirements. In comparison, solid-state varactor [5] and liquid crystal [6] based TTD units suffer from high insertion loss whereas active phase-rotator based phase shifters [7] provide insufficient phase resolution, relatively low bandwidth, and high power consumption. In this work, we demonstrate a high performance RF-MEMS based true-time-delay line with analog tuning capabilities for 30–50 GHz.

II. Design

A. Extended Tuning Range Varactor

Existing MEMS-based phase shifter designs predominantly use electrostatic actuators whose tuning range is limited to a theoretical ratio of 1.5:1 by the pull-in effect, which further results in either a limited delay range or a digital tuning design with low resolution. In order to achieve a large delay with fine resolution, we choose to use an extended tuning range varactor design[8], in which the actuation gap d_0 (Fig. 2) is more than three times the capacitance gap g_0. This configuration can achieve a theoretical capacitance tuning ratio of infinity. In practice, the tuning ratio is limited by surface roughness, fringing-field capacitance, and the limited resolution of the bias voltage supply. In this design, a cantilever type varactor with g_0 of $1\,\mu$m and d_0 of $4\,\mu$m is chosen for fine resolution and reasonable bias voltage (<200 V).

B. Impedance Matching

The design of a varactor-loaded-line phaseshifter starts with a high impedance (Z_h) transmission line in the un-loaded state. As the loading capacitance increases, the characteristic impedance of the line decreases. The desired return loss specification sets the upper limit of Z_h and the tuning range. Conventional designs use a uniform distribution of capacitance. In this design, however, a tapered capacitance distribution is used to improve the impedance matching at the highly loaded states so that tuning range could be improved.

Taking into account the above design considerations, the final design consists of 33 cantilever-type extended tuning range varactors loaded on a CPW line of 140/42/140 µm on a high-resistivity silicon substrate. The input and output of the CPW line are tapered to accommodate 150 µm-pitch GSG probes. The nominal dimensions of the actuators are shown in Fig. 2 c, which results in a pull-in voltage of 170 V when the beam thickness is 2 µm. The width of the RF capacitance portion of the varactors are tapered according to the following: $w_1 = w_{33} = 23\,\mu\text{m}$, $w_2 = w_{32} = 30\,\mu\text{m}$, $w_3 = w_{31} = 35\,\mu\text{m}$, $w_4 = w_{30} = 37\,\mu\text{m}$, $w_5 = w_{29} = 38\,\mu\text{m}$, w_6–$w_{28} = 39\,\mu\text{m}$. With a varactor spacing of 100 µm, this results in a worst case Bragg frequency of 190 GHz. Fig. 3 shows a comparison between the uniformly loaded and the tapered design.

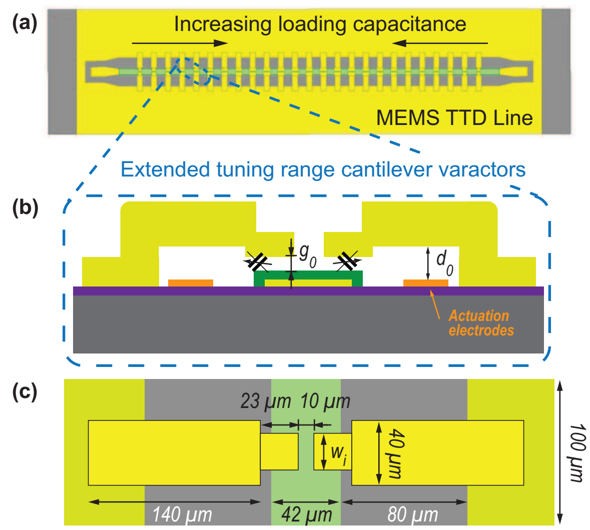

Fig. 2. (a) MEMS-based TTD line; (b) Extended tuning range cantilever-type varactor design; (c) Critical dimensions of the cantilever actuators.

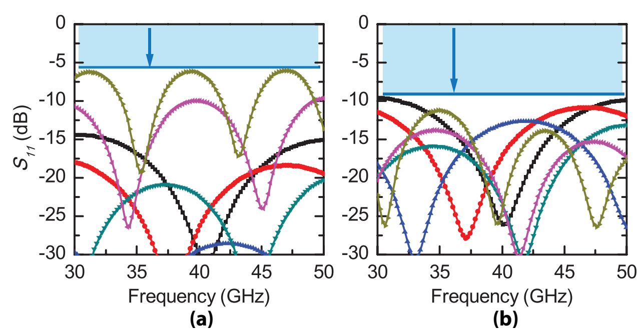

Fig. 3. Simulated S_{11} of the proposed TTD before and after impedance matching with tapered loading.

III. Fabrication & Measurements

The proposed device is fabricated with standard surface micromachining techniques (Fig. 4). The process starts by patterning the SiCr bias lines, coplanar waveguide (CPW) lines, and the bias electrodes using photolithography and a combination of etch back and lift-off (Fig. 4-a). Two photoresist sacrificial layers (AZ5214E and S1827) are then used to define g_0 and d_0 (Fig. 4-b). After an electroplating step (Fig. 4-c) to form the cantilever beam, and the device is released in a critical point dryer (Fig. 4 d). Fig. 4-e&f show scanning electron microscope images of the fabricated device with a close-up view of the cantilevers.

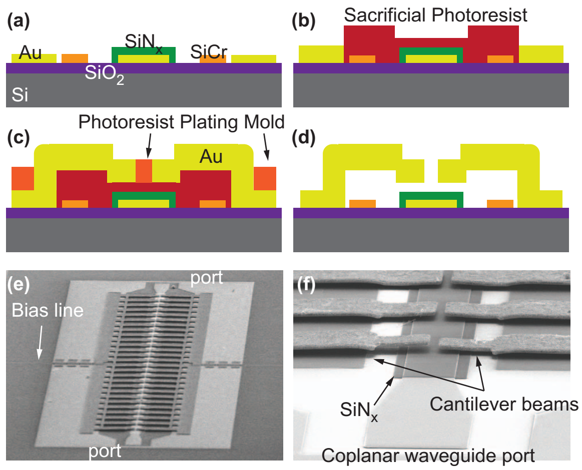

Fig. 4. Fabrication process of the MEMS-based TTD lines. Detailed explanations are provided in Section III.

The device is measured without a package on a probe station using an Agilent network analyzer. A single bias voltage is applied to all the cantilevers simultaneously. As designed, the device exhibits an analog tuning range without pull-in for below 170-V bias. The magnitude of the measured S_{11} and S_{21} under several states across the tuning range the are shown in Fig. 5. Better than 10-dB return loss is maintained in nearly all tuning states. This agrees very well with the design (Fig. 3).

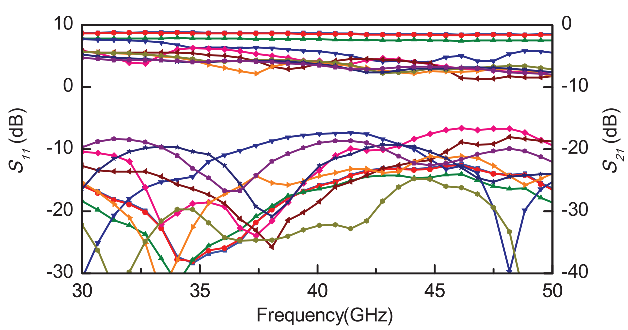

Fig. 5. Measured S-parameters of the fabricated TTD line.

The measured phaseshift of the device under several bias voltages is shown in Fig. 6. Although only a few curves are shown, the tuning is in fact analog and the tuning resolution is only limited by the resolution of the voltage power supply. A nearly linear phase vs. frequency relationship is observed across the 30–50 GHz frequency band in all states (Fig. 6). The maximum phase shift exceeds 360° at 30 GHz and reaches 600° at 50 GHz. The figure of merit (FoM) in terms of phaseshift per dB of insertion loss is between 60°/dB and 80°/dB. The device exhibits near constant delay that can be adjusted between 0 and 33 ps in an analog fashion. To the authors' knowledge, this is the best TTD unit demonstrated to date in terms of maximum adjustable delay range and FoM in this frequency range.

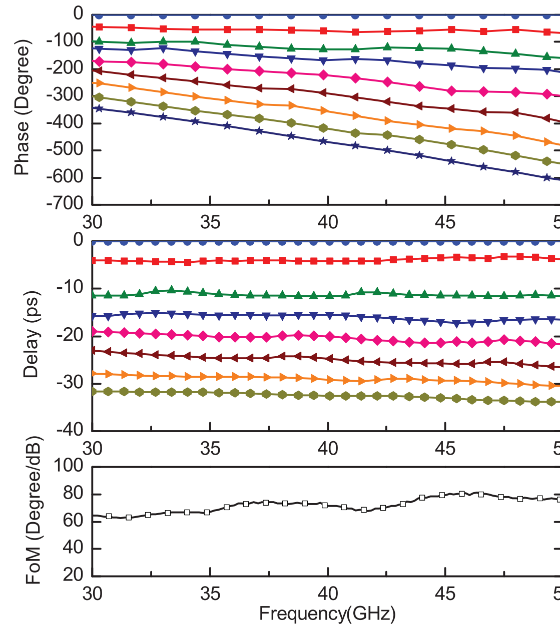

Fig. 6. Measured (a) phaseshift (b) delay (c) FoM of the fabricated TTD line.

IV. Conclusion

Using a combination of an extended tuning range varactor and a tapered loading scheme, we have successfully demonstrated an RF-MEMS based true-time-delay line with more than 360° phaseshift (30 ps delay) and a FoM better than 60°/dB across the entire 30–50 GHz band. The TTD unit will significantly improve both the spatial and temporal resolution of an MIR imaging system for diagnostics of fusion plasmas. Future work includes incorporating low-loss packaging and extending the operation range to beyond 80 GHz.

References

[1] E. Mazzucato, "Microwave imaging reflectometry for the visualization of turbulence in tokamaks, " *Nuclear Fusion*, Vol. 41, No. 2, pp. 203. doi:10.1088/0029-5515/41/2/307

[2] C. M. Muscatello et al., "Technical overview of the millimeter-wave imaging reflectometer on the DIII-D tokamak (invited)," *Rev. Sci. Instrum.* 85, 11D702 (2014). http://dx.doi.org/10.1063/1.4889735

[3] J. E. Menard et al., "Overview of the physics and engineering design of NSTX upgrade," *Nuclear Fusion*, Vol. 52, No. 8, 083015, 2012.

[4] J. Li et al., "A long-pulse high-confinement plasma regime in the Experimental Advanced Superconducting Tokamak," *Nature Physics*, Vol. 9, pp. 817–821, 2013.

[5] A. S. Nagra, J. Xu, E. Erker and R. A. York, "Monolithic GaAs Phase Shifter Circuit with Low Insertion Loss and Continuous 0–360° Phase Shift at 20 GHz," *IEEE Microwave and Guided Wave Letters*, Vol. 9, No. 1, pp. 31–33, Jan., 1999.

[6] T. Kuki, H. Fujikake, H. Kamoda, and T. Nomoto, "Microwave variable delay line using a membrane impregnated with liquid crystal," *IEEE MTT-S International Microwave Symposium Digest*, 2002.

[7] K-J. Koh and G. M. Rebeiz, "0.13 μm CMOS Phase Shifters for X-, Ku-, and K-Band Phased Arrays," *IEEE JOURNAL OF SOLID-STATE CIRCUITS*, VOL. 42, NO. 11, NOV., 2007.

[8] J. Zou, C. Liu, et al.,"Development of a wide tuning range MEMS tunable capacitor for wireless communication system," *Technical Digest of International Electron Devices Meeting*, pp. 403–406, 2000.