A High-Q W Band Tunable Bandpass Filter

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***Abstract*—We present a tunable high-Q two pole waveguide bandpass filter at 110 GHz. The demonstrated filter has record performing insertion loss (2 dB) and tuning range (11 GHz) in the W band (75–110 GHz). A sub-micron resolution piezo electric stepper motor is used to actuate a thin film which forms the ceiling of the resonant cavities. This sub-micron actuation effectively tunes the center frequency of the filter. This tunable filter has a variety of uses such as a front-end bandpass filter for multi-band communications, as a filter for rejecting intermodulation products on tunable systems or as a channel select filter.**

***Index Terms*—millimeter wave circuits, Bandpass filters, tunable filters.**

I. Introduction

Millimeter wave technology has seen significant advancement in the last decade primarily due to growing interest in wide bandwidth communications, wide bandwidth vehicle collision avoidance systems and non-ionizing high resolution imaging for security systems. More established uses of mm wave technology include chemical spectroscopy, radio astronomy and military radar.

Generation of millimeter waves often involves frequency multiplication due to the lack of stable high power sources at these frequencies. Frequency multiplication is a non-linear process which relies on harmonic generation to produce the desired frequency. Unfortunately, this process creates a multitude of unwanted spurious signals and intermodulation products with every additional non-linear frequency multiplier or amplifier that is cascaded in a system. These spurious signals pose significant interference in multi-band millimeter wave communications and many of the other aforementioned developing technologies which involve dynamic or multi-band millimeter wave frequencies. Frequency multiplication is also a highly inefficient process and significant power is lost with every multiplication step. Therefore, it is critical that passive components exhibit low insertion loss and a high quality factor at these frequencies.

Several approaches to millimeter wave tunable bandpass filters have been developed to overcome these challenges [1-4]. Evanescent mode cavities have been configured in several low frequency filter designs and have exhibited high quality factor and tuning range [2, 5-6]. We demonstrate a tunable bandpass filter composed of two evanescent mode cavity resonators in bandpass configuration with record performing insertion loss and tuning range in the W band. This paper describes the design methodology, fabrication, assembly and calibrated measurements of the WR10 tunable bandpass filter.

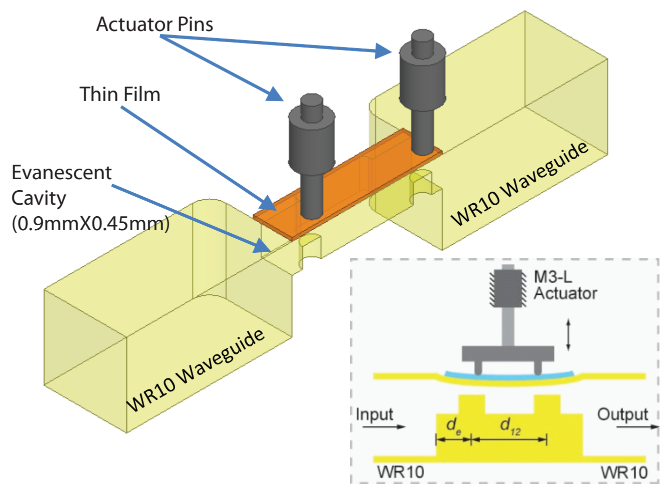


Fig. 1. Cross section of the W band tunable filter.

II. Design of a WR10 Tunable Resonator

Fig. 1 shows the cross-section design of the WR10 tunable filter. The tunable filter is comprised of two resonators which are coupled to rectangular waveguide. Each resonator is an evanescent mode cavity with a metallic post in the center which can be modeled as a series RLC circuit [2, 5-7]. A gap between the top of the post and ceiling of the cavity (thin conductive film) forms the capacitor of the RLC circuit and the post forms the inductor. As shown in Fig. 1, a sub-micron precision M3-L actuator from Newscale Technologies is used to flex the thin film which forms one plate of the capacitor. As the plate flexes, the effective gap of the capacitor, d, varies and this is inversely proportional its capacitance C. Thus, the resonant frequency ω of each resonator is tuned by actuating the thin film. The capacitance C of the resonator is designed such that an actuation of 130 μm tunes the filter from 75 GHz to 110 GHz. Low loss rectangular waveguide is used to couple to and from the resonator via the H-fields of the TE10 electromagnetic waves in the waveguide. The resonator design is the building block of the two-pole filter. To measure the unloaded quality factor Q_U of the resonators, a WR10 tunable resonator was micro-machined in an aluminum split block via precision CNC machining and a gold-plated silicon thin film was fabricated. Fig. 2a shows the assembled tunable resonator.

III. Tunable Resonator Fabrication

Silicon was chosen for its high yield strength and high youngs modulus [8]. This ensures that the film can be flexed to a large degree and that the film will return to its original position when the actuator is released. The thin film is fabricated on an SOI wafer with a thin silicon device layer ($5\,\mu\mathrm{m}$). At $100\,\mathrm{GHz}$, the skin depth of gold is approximately $0.236\,\mu\mathrm{m}$. Therefore, the wafer was patterned and then plated with $1.4\,\mu\mathrm{m}$ of gold. After etching the silicon around the gold patterned area, the films were released by removing the underlying oxide layer with chemical etchant. The base half of the machined block was copper sputtered to improve the unloaded Q of the cavity as well as the insertion loss of the waveguides. The precision machined dimensions are within $10\,\mu\mathrm{m}$ tolerance of the designed values and the finish has low surface roughness ($<1\,\mu\mathrm{m}$). This is necessary to obtain the high Q resonator profile and the 75–110 GHz tuning range.

IV. Measurement of a W Band Tunable Resonator

The resonator was tested using OML W-band extender modules and an Agilent PNA-X. The extender modules were calibrated using short, through line and delayed through line calibration standards. As shown in Fig. 2b, the resonator can be tuned from 75–110 GHz by actuating the film by $130\,\mu\mathrm{m}$. Fig. 2c shows the Q_U at various frequencies. The insertion loss of a 0.75 inch aluminum H-plane split waveguide straight section was measured to approximate the loss of the H-plane split waveguide of the tunable resonator. This loss was practically negligible (0.02dB).

V. Design and Fabrication of a WR10 Tunable Band Pass Filter

To achieve low insertion loss, a flat passband and a steep roll-off, we determined the required inter-resonator coupling coefficient k_{12} and the external quality factor Q_e. A high Q_e results in a filter profile with steep roll-off albeit with high insertion loss. Fig. 3a shows the variation of Q_e with respect to distance d_e between the coupling WR10 waveguide and the evenascent-mode loading post (Fig. 1 inset). To achieve low insertion loss, d_e was designed at $0.6\,\mathrm{mm}$. The coupling between the resonators is dependent on the dimension, d_{12} from Fig. 1 and this determines the bandwidth and the flatness of the filter passband. Strong coupling, k_{12}, between the resonators widens the bandwidth of the filter, however, this profile will have a large dip in the middle of the pass band. If k_{12} is too low, the insertion loss of the filter suffers. Fig. 3b shows the variation of k_{12} with the dimension d_{12}. We have selected d_{12} at $1.7\,\mathrm{mm}$ to form a passband with a flat profile and low insertion loss. ANSYS HFSS finite element solver was used to model and simulate the filter. Fig. 4 shows the simulation results of the filter with a tuning range of 75–110 GHz over an actuation of 0-$125\,\mu\mathrm{m}$. A post with two pins was precision-machined and integrated with the M3-L actuator. The M3-L actuator has a force of $0.3N$ and step resolution of $0.5\,\mu\mathrm{m}$. A precision frame was machined with the cover block so that the M3-L actuator aligns well with the resonators. The passband profile of the filter is very sensitive to any difference in the resonators so it is critical that the alignment of the actuators is precise so that the capacitors of the resonators are tuned equally. The filter was assembled by clamping the thin silicon film in between the aluminum block halves. Fig. 5a shows the assembled filter with integrated M3-L and two-pin actuator.

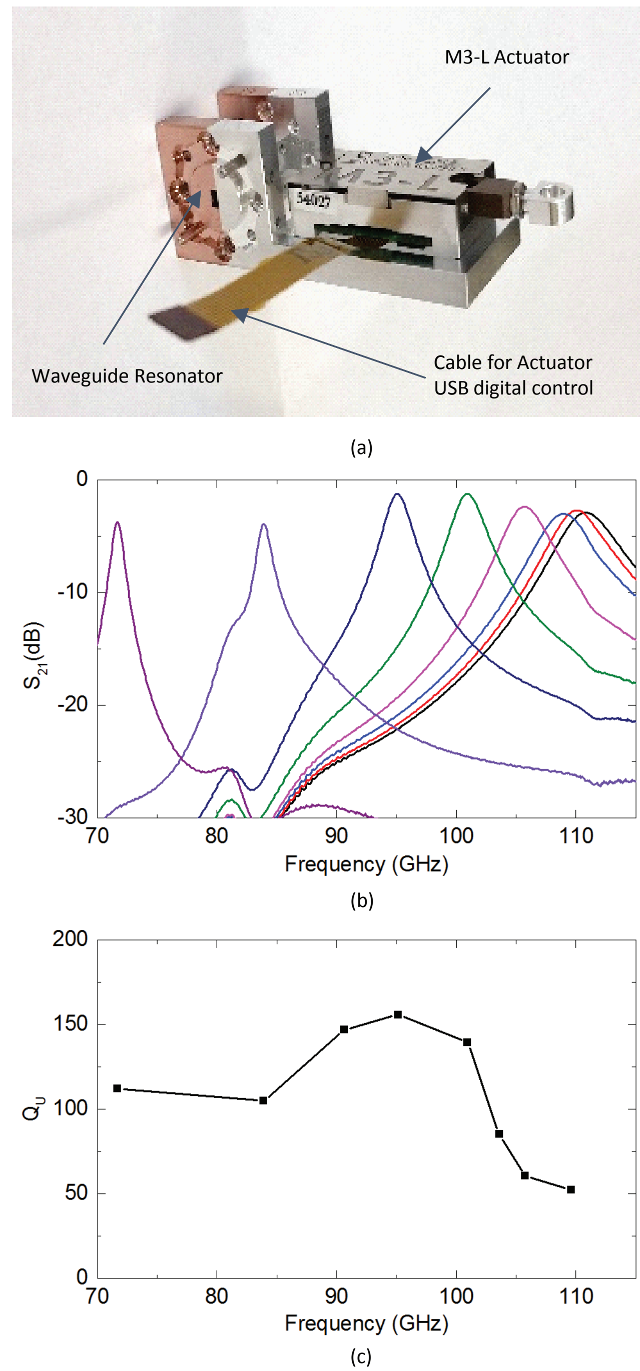
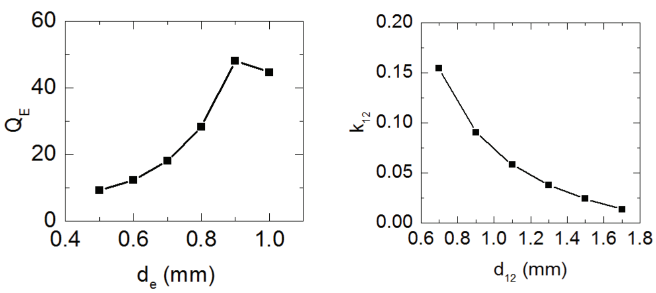


Fig. 2. (a) Assembled WR10 tunable resonator. The M3-L actuator is integrated onto the cover half of the block and the base half is copper coated; (b) Measured S_{21} of the WR10 tunable resonator; (c) Q_U of the WR10 tunable resonator.

TABLE I
COMPARISON WITH STATE OF THE ART.

Work	Center Frequency (GHz)	Tuning Range (%)	Insertion Loss (dB)	Tuning Mechanism
[1]	95	7	2.37	Air pressure based mechanical deflection
[3]	38	5	4	Electromagnetic crytal varactors
[4]	65	2.34	9.7	MEMs
This work	107	10	2	Piezo-electric Stepper Motor



(a) (b)

Fig. 3. (a) Q_e of the filter as a function of de; (b) k_{12} of the filter as a function of d_{12}.

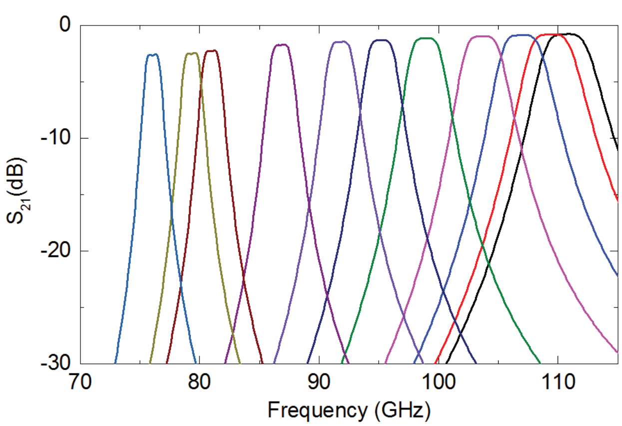
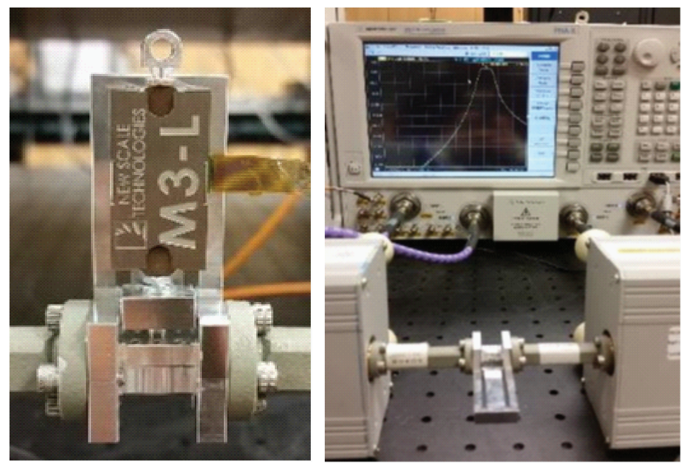


Fig. 4. Simulated performance of the filter with various actuation positions.

VI. MEASUREMENT OF A TWO POLE BAND PASS FILTER

The filter was measured using OML W band extender modules and an Agilent PNAX with a similar calibration as previous. The M3-L actuator was stepped from 0–70 µm via USB control while measuring the S-parameters of the filter. Fig. 5b shows the measurement setup (M3-L actuator not yet integrated) and Fig. 6 shows the measured data of the filter. The insertion loss of the pass band is < 2 dB and we were able to tune the filter by 11 GHz. The tuning range was limited by the thin films which were unable to actuate further than 70 µm without breaking.



(a) (b)

Fig. 5. (a) Assembled WR10 Tunable Filter; (b) Filter measurement setup (M3-L actuator not shown).

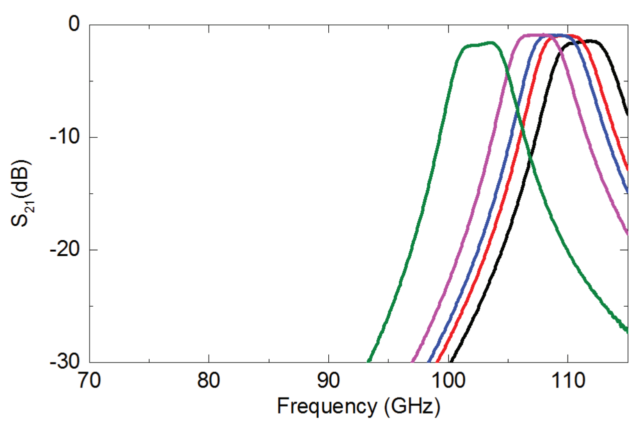


Fig. 6. Measured performance of the filter with various actuation positions

VII. CONCLUSION

We have demonstrated the design and fabrication of a record performing tunable filter at W band with < 2 dB insertion loss and tuning range of 11 GHz. The tuning range can be improved by re-designing the thin actuated films to tolerate a larger actuation and the Q_U and insertion loss of the filter can be improved by gold plating the aluminum block. Table 1 shows a comparison of similar work. This design demonstrates record performance with the potential for even better tuning range and insertion loss. The piezo electric stepper motor based tuning mechanism is also fast and repeatable. This design can be scaled to higher sub-millimeter wave frequencies as the machining precision required for the design is not yet close to pushing the limits of machining capability. Higher frequency designs will also require a smaller actuation to achieve the same percentage tuning range which will mean less stress on the thin films. The strong performance of this filter design can improve signal to noise ratio as well as the SFDR in multi-tone and dynamic frequency millimeter wave systems without significant cost to RF power.

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