Varactor-Tunable Uniplanar Ring Resonators

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***Abstract*—In this paper, slotline and CPW ring resonators are introduced and integrated with varactor diodes to create electronically tunable uniplanar ring resonators. Varactors electronically tune the second resonant mode of the slotline ring over a 23% bandwidth from 3.03 to 3.83 GHz with a 4.5 ± 1.5 dB variation in insertion loss. Similarly, a CPW ring resonator was tuned over a 22% bandwidth from 2.88 to 3.59 GHz. Both resonators offer the ground plane and center conductor on the same side of the substrate to allow easy series or shunt insertion of solid-state devices. DC biasing is naturally integrated in the slotline structure and straight forward in CPW. Monolithic implementation of these resonators would not require via holes to ground solid-state devices which should reduce processing complexity and increase production yields.**

I. Introduction

Resonators form the basic design elements in many circuit components including filters, oscillators, couplers and antennas. Planar resonators offer several advantages over conventional rectangular/circular waveguide resonators including size, weight and cost. Planar resonators that can be easily integrated with solid-state devices like varactors, PINs and FETs provide low-cost alternatives for switchable/tunable filters, amplifiers, oscillators and active antennas. Although most linear and ring planar resonators have been realized in microstrip, other planar transmission lines such as coplanar waveguide(CPW) and slotline may offer some useful advantages.

The microstrip ring resonator was introduced by Troughton [1] in 1968. Since its introduction, the microstrip ring resonator has been used in determining guided wavelength (λg) [2], [3], effective dielectric constant ($\epsilon_{\rm eff}$) [4], equivalent circuits for discontinuities [5], and relative dielectric constant (ϵ_r) [6]. Microstrip ring resonators allow easy series insertion of solid-state devices for tuning [7]–[9], switching [10], and RF power generation [11]. They provide a low-loss, compact quasi-TEM propagation mode with easy transition to coax and simple design of test fixtures. Some drawbacks of using microstrip include sensitivity to substrate thickness, difficulty of inserting shunt solid-state devices, and the design of high-impedance lines for dc biasing. Although microstrip is the most mature and widely used planar transmission line, other forms of transmission lines are available for flexibility in circuit design. These uniplanar transmission lines include CPW, slotline and coplanar strips (CPS). The characteristics of these transmission lines are listed in [12, p. 299].

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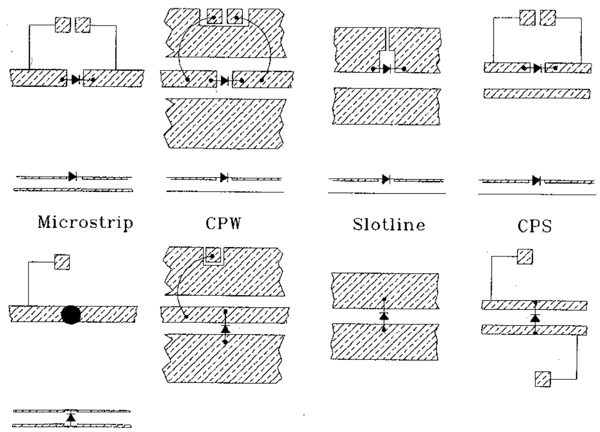

Fig. 1. Series/shunt diode insertion and biasing on several planar transmission lines.

In recent years, coplanar waveguide has emerged as an alternative to microstrip in microwave and millimeter-wave hybrid (MIC) and monolithic (MMIC) integrated circuits. The center conductor and ground planes are on the same side of the substrate to allow easy series and shunt connections of passive and active solid-state devices [13]. Use of CPW also circumvents the need for via holes to connect the center conductor to ground and helps to reduce processing complexity in monolithic implementations. Fig. 1 shows possible mounting and biasing configurations for series and shunt devices on microstrip, slotline, CPW and CPS.

Using CPW, slotline and CPS for new uniplanar resonators may be important for design flexibility in many filter, coupler, oscillator and antenna applications. Many shapes have been used in microstrip which include linear, disk and ring resonators. Linear CPW resonators were used in [14], [15] for band-pass filter applications. Slotline sections have been used for filters [15], couplers [16] and antennas [17], [18]. Slotline rings have been implemented in a frequency selective surface [19]. In this paper, we introduce slotline and CPW ring resonators for tunable filter applications. These configurations allow easy device insertion and dc biasing.

Two uniplanar ring resonators were developed with over 20% varactor tuning range and moderate insertion loss. The uniplanar rings use slotline and CPW transmission lines. Their tuning ranges are wider and the configurations offer greater flexibility over the microstrip rings in [7]–[10]. Microstrip, for instance, requires high impedance lines at specific locations to apply dc biasing and a series gap fixes the position of the varactor along the ring. Furthermore, shunt varactor insertion requires drilling through the substrate in hybrid MICs or via hole processing in MMICs.

The slotline ring circuit configuration, on the other hand, offers inherent dc biasing pads without the need for filtering capacitors. Shunt diodes can be optimized along the ring circumference. Although the CPW ring requires bias lines similar to microstrip and a cover to remove even modes, it is not sensitive to substrate thickness and two solid-state devices can be placed at the same node point along the ring. The CPW ring can have greater capacitance range and lower diode resistance loss by using two varactors at the same tuning node. Both uniplanar configurations are amenable to other device integration for switching, tuning, mixing and RF power generation.

II. Ring Circuit Design and Model

Ring resonator design requires the determination of the guided wavelength (λ_g) of the transmission line used. The ring will resonate when its mean circumference is a multiple of the guided wavelength

$$2\pi R = n\lambda_g \quad n = 1, 2, 3, \cdots \tag{1}$$

where R is the mean ring radius and n is the mode number.

The microstrip ring has been analyzed with many different methods:

1) T and π-equivalent circuits [9, 10].
2) Magnetic wall model [20].
3) Field solutions [21]
4) Numerical solutions [22]
5) Distributed transmission line [23].

Each method of analysis determines the resonant frequencies of the modes of the resonator. The methods vary in accuracy and computing time requirements. The field, numerical and magnetic-wall methods often require large storage space and computing speed but provide little flexibility in incorporating solid-state devices. The equivalent circuit method provides a simple and quick analysis and facilitates the introduction of solid-state devices placed arbitrarily along the ring.

The distributed transmission line method provides a simple and straight forward solution with little computer time requirements. Solid-state devices can be inserted easily along the circumference of the ring. Closed form solutions or curve-fitted expressions for the parameters of the transmission line ring are used. These parameters are used in a circuit simulation program such as Touchstone or Microwave Spice. The S-parameter or input impedance results are found easily and quickly with minimal storage requirements. Overall accuracy of the resonant frequencies depends on the transmission line parameters used.

The ring equivalent circuit for a varactor tunable ring is shown in Fig. 2. The ring is divided into many sections of transmission lines for the analysis [23]. The field distribution at the resonant frequencies along the ring depends on the feeding method used. Several feeding [24] configurations are shown in Fig. 3. For symmetrical feeds without any asymmetrical perturbations along the ring, single mode operation at each resonant frequency is assured. The electric field distribution for the capacitive feeds vary according to:

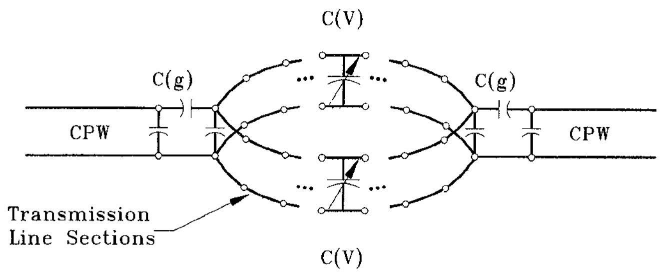

Fig. 2. Ring resonator distributed transmission line equivalent circuit.

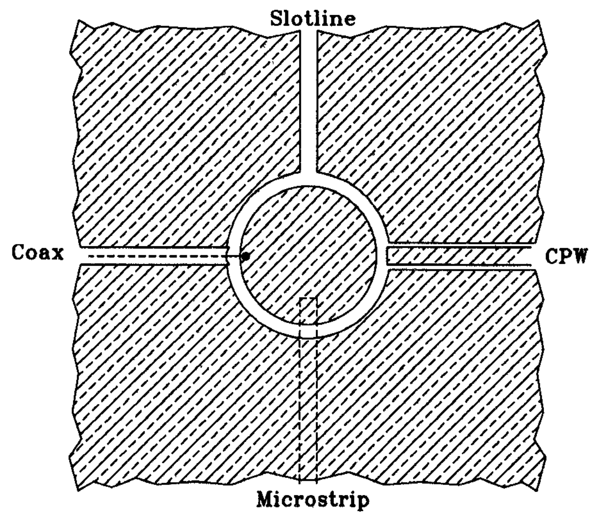

Fig. 3. Several possible feed configurations for slotline ring resonators.

$$|E| \approx \cos(n\varphi) \quad n = 1, 2, 3 \cdots \tag{2}$$

Fig. 4 shows the field distribution for the first four resonant modes of the ring resonator. Even or odd multiple-wavelength standing waves are set up along the resonator. By proper placement of devices, one can selectively choose to match, tune, or switch-off even/odd resonant modes. Fig. 4 shows that diodes at 90 and 270 degrees will greatly affect even resonant modes but have little effect on odd resonant modes. For our design, varactors at these positions serve to tune the second resonant mode. The first and third modes are unaffected. Furthermore, the varactors must be placed symmetrically for single mode operation and avoid split mode effects [25].

The equivalent circuit of a varactor diode and the reactance curves at 0 and 30 volts are shown in Fig. 5. The parasitic effects are also shown. The junction capacitance ($C_j(V)$) behaves as

$$C_j(V) = \frac{C_{j0}}{\left(1 + \frac{V}{V_{bi}}\right)^{\gamma}} \tag{3}$$

where C_{j0} = 1.6 pF, V_{bi} is the built-in potential of 1.3 volts for GaAs [26], γ is the capacitance-voltage slope exponent of 0.5 for abrupt-junctions and V is the applied reverse-bias varactor voltage.

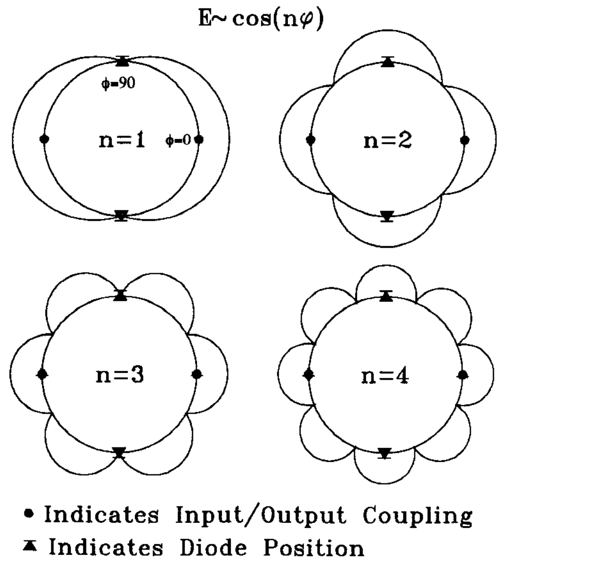

Fig. 4. Electric field distribution for different modes along a ring resonator.

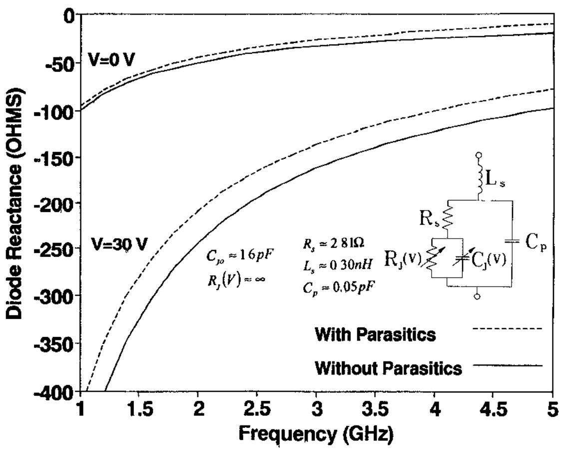

Fig. 5. Varactor equivalent circuit and impedance with and without parasitics.

III. The CPW-Fed Slotline Ring Resonator

Fig. 6 shows the CPW-fed slotline ring configuration. A distributed transmission line model shown in Fig. 2 was used to analyze the slotline ring. A 50 Ω CPW line feeds an 85 Ω slotline ring through a series gap. The gap can be represented by a capacitor which controls the coupling efficiency into the slotline ring and is inversely proportional to the gap spacing. The effect of the size of the coupling gap is shown in Fig. 7 for two gap sizes of approximately 0.50 and 0.05 mm. The 0.05 mm gap reduces the insertion loss by increasing the coupling into and out of the resonator. The ring has a mean radius of 11.26 mm and uses a 0.50 mm slotline on a 0.63 mm thick RT-Duroid 6010 substrate. The relative dielectric constant is 10.5.

Fig. 8(a) shows the theoretical and experimental insertion loss for a 0.05 mm gap. The theoretical results were obtained based on the equivalent circuit shown in Fig. 2. The slotline ring is formed by cascading many small sections of slotlines

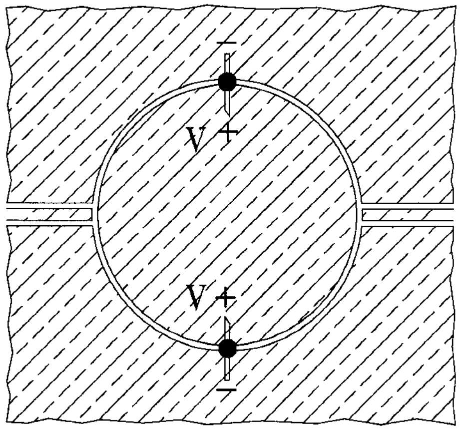

Fig. 6. The varactor tunable slotline ring configuration.

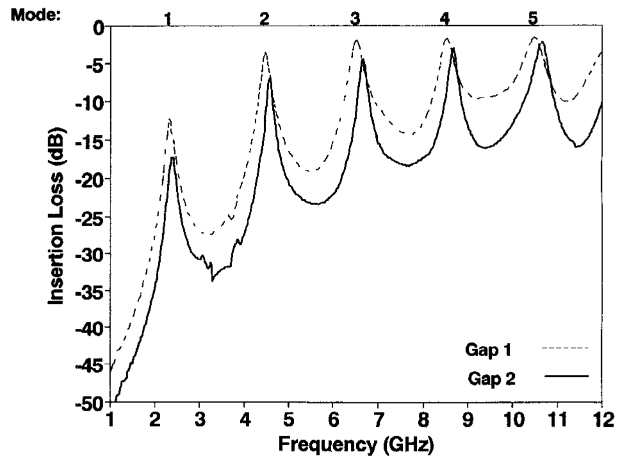

Fig. 7. Effect of gap spacing on input/output coupling to slotline ring. Gap 1 is 0.05 mm and Gap 2 is 0.50 mm.

together. The input coupling gap is approximated using a small series capacitor. The transmission line parameters were determined based on formulas in [12, p. 215]. The gap capacitances were determined empirically from measurements. The theoretical results agree fairly well with measurement over a wide bandwidth. The errors for resonant frequencies are within 1.2%. Fig. 8(b) shows the return loss which indicates the typical input matching condition.

IV. Varactor Tuning Results for Slotline Ring

The varactors located at 90 and 270 degrees along the ring tune the even modes of the resonator and allow a second mode electronic tuning bandwidth of 940 MHz from 3.13 to 4.07 GHz for varactor voltages of 1.35 to 30 volts. Fig. 9(a) shows the experimental results. The first peak is for the first mode which is stationary during the electronic tuning. A return loss of 6.4, 7.7 and 8.5 dB was achieved for varactor voltages of 5, 10 and 30 V, respectively. Improved return loss could be achieved using matching elements at the coupling points. Fig. 9(b) shows a comparison between the theoretical and the actual tuning range with reasonable agreement. The increase in loss as the frequency is lowered is due, in part, to a reduction in

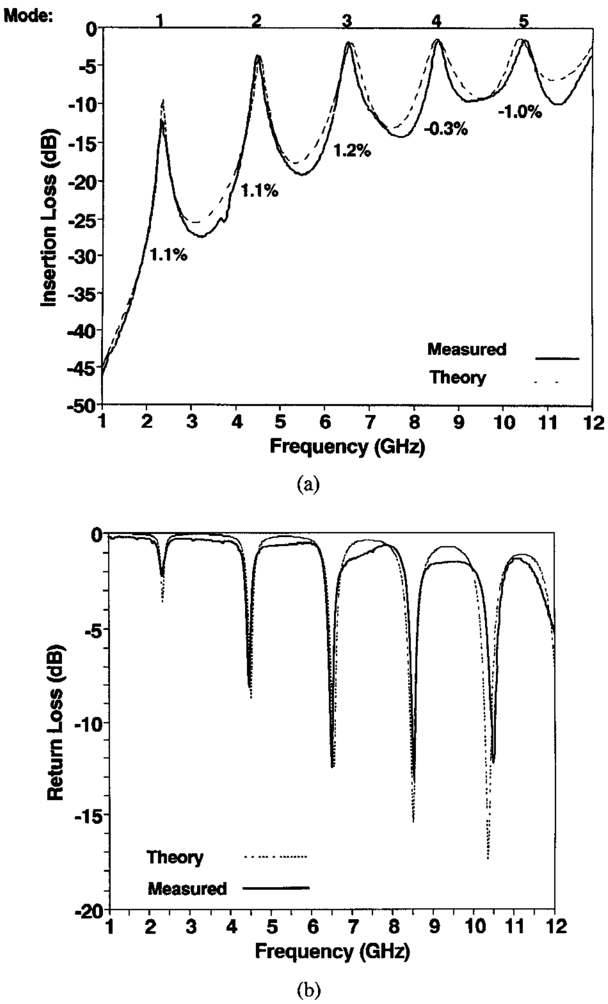

Fig. 8. Theoretical versus measured insertion loss and resonant frequencies of a slotline ring resonator.(a) Insertion loss. (b) Return loss.

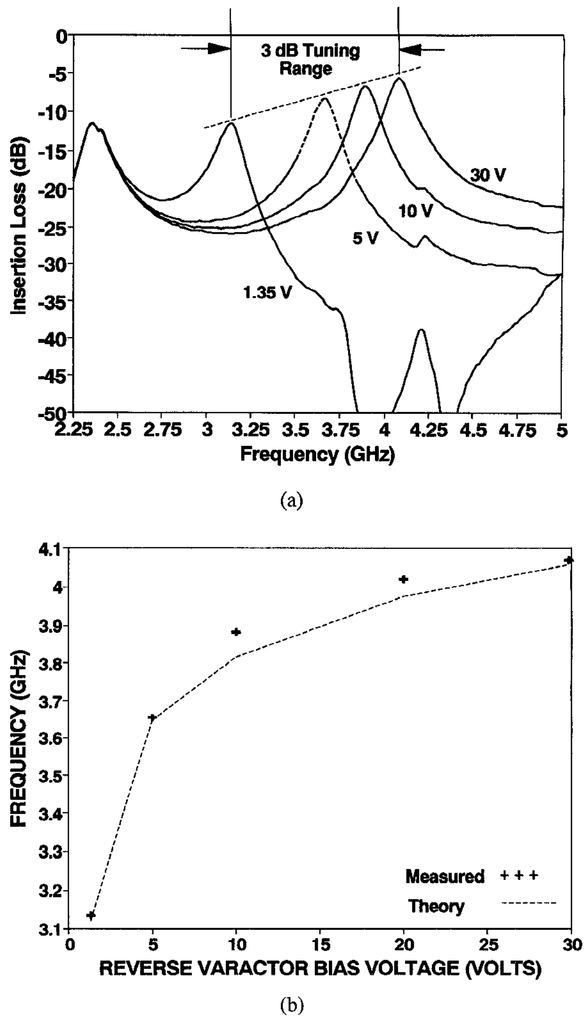

Fig. 9. Varactor tuning the of second resonant mode of a slotline ring resonator. (a) Measured insertion loss for different varactor voltages. (b) Theoretical versus measured second resonant mode frequency as a function of varactor voltage.

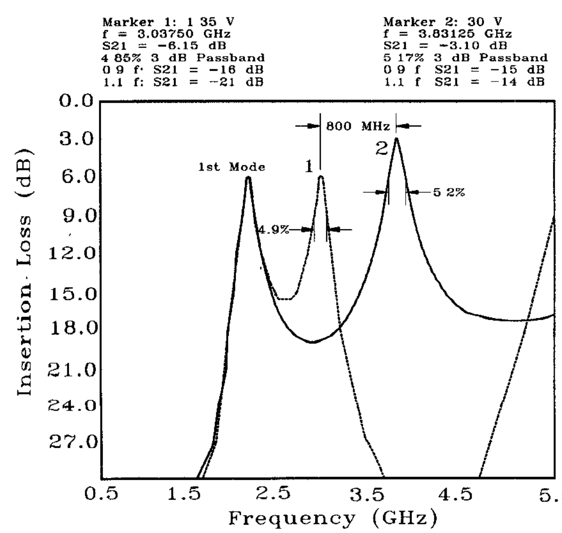

Fig. 10. Measured varactor tuning range of a slotline ring with dielectric overlays over the coupling gaps.

input/output coupling. The loss increases linearly from 6 dB at 4.07 GHz to 11 dB at 3.13 GHz.

In order to reduce the insertion loss, a $3 \times 3 \times 0.3$ mm capacitive overlay [14] placed over the input and output of the slotline ring was used to increase the coupling and reduce the discontinuity radiation. This overlay reduced the loss and slightly lowered the frequencies of operation due to greater capacitive loading. The tuning bandwidth becomes 3.03 to 3.83 GHz. The 800 MHz tuning range centered at 3.4 GHz is shown in Fig. 10. As shown, the overlay helps to improve the insertion loss of the tunable resonator. The 23% tuning range from 3.03 to 3.83 GHz has an insertion loss of 4.5 dB $\pm$ 1.5 dB for varactor voltages of 1.35 to 30 volts. As shown in Fig. 10, the varactors have little effect on the first mode of the slotline ring resonator while capacitively tuning the second mode. The 3 dB points on the pass band vary from 4.85% at 3.03 GHz to 5.17% at 3.83 GHz. The insertion loss at $\pm$10% away from the second mode resonant frequency is about $\geq$15 dB. The increase in insertion roll-off for the lower frequency end of the tuning range is due to the stationary third mode. As the varactor bias level is lowered further, the second mode continues to approach the stationary first mode.

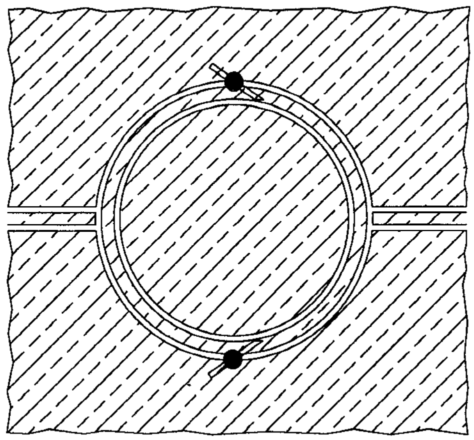

Fig. 11. The varactor tunable CPW ring configuration.

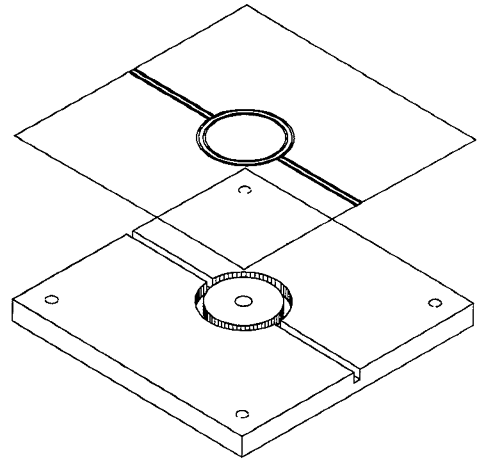

Fig. 13. The enclosure for the CPW ring assembly.

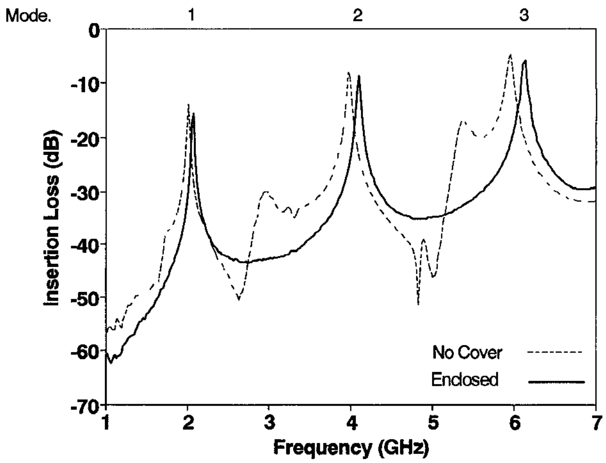

Fig. 12. Insertion loss of a CPW Ring with even and odd modes propagating.

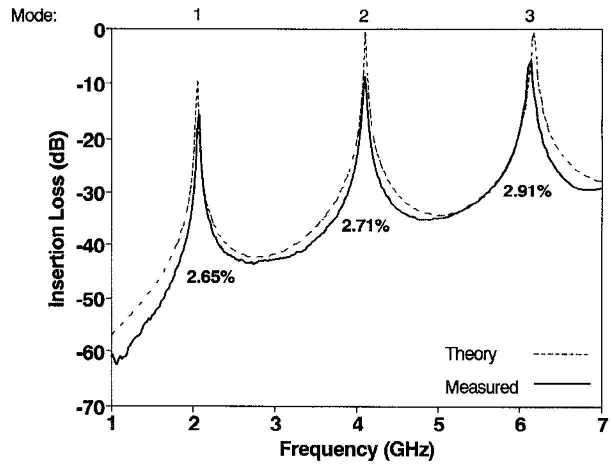

Fig. 14. Theoretical vs measured insertion loss and resonant frequencies of a CPW ring resonator.

V. The CPW Ring Resonator

The CPW-fed CPW ring configuration is shown in Fig. 11. The CPW ring is divided into many sections and the equivalent circuit shown in Fig. 2 is used for analysis. Two 50 Ohm CPW lines feed the CPW ring via a series gap. The ring has a mean diameter of 21 mm and uses 0.5 mm slotlines spaced 1.035 mm apart on 0.635 mm RT-Duroid 6010 substrate with a relative dielectric constant of 10.5. The resonant frequencies are found using equation (1).

Fig. 12 shows that the performance of the CPW ring is corrupted by the propagation of even coupled slotline modes along the ring. To suppress these unwanted modes, the center disk of the ring must be maintained at ground potential. Wire bonding can be used at the input and output of the ring and along the ring itself to maintain the center disk ground potential but may prove to be labor intensive. A cover serves to maintain the center disk at ground potential all along the circumference of the ring as well as seal and protect the circuit. The enclosure suppresses all even mode propagation and reduces its inductive effect on the CPW odd mode. The enclosure and assembly shown in Fig. 13 avoids wire bonding and soldering but requires alignment and good pressure contact with the ring. The height and width of the enclosure do not require high-tolerance machining.

Fig. 14 shows the theoretical and measured results for the enclosed CPW ring. The theoretical results were obtained based on the equivalent circuit shown in Fig. 2. The transmission line parameters were determined based on formulas in [12, p. 275]. The gap capacitances were determined empirically. The agreement is within 2.91%.

VI. CPW Ring Varactor Tuning Results

Advantages of the CPW ring over the slotline ring are that both series and shunt devices can be mounted easily along the ring and two shunt varactors can be placed at each circuit point to increase the tuning range and reduce the diode real resistance. A varactor and PIN diode can be placed at a single node to obtain switching and tuning with the same ring resonator.

The varactors located at 90 and 270 degrees along the ring tune the even modes of the resonator and allow a second resonant mode electronic tuning bandwidth of 710 MHz from 2.88 to 3.59 GHz for varactor voltages of 0 to 30 volts. Fig. 15(a) shows the experimental results and Fig. 15(b) shows a comparison of theoretical and measured resonant frequency at different varactor bias levels. The increase in loss as the frequency is lowered is due, in part, to a reduction in

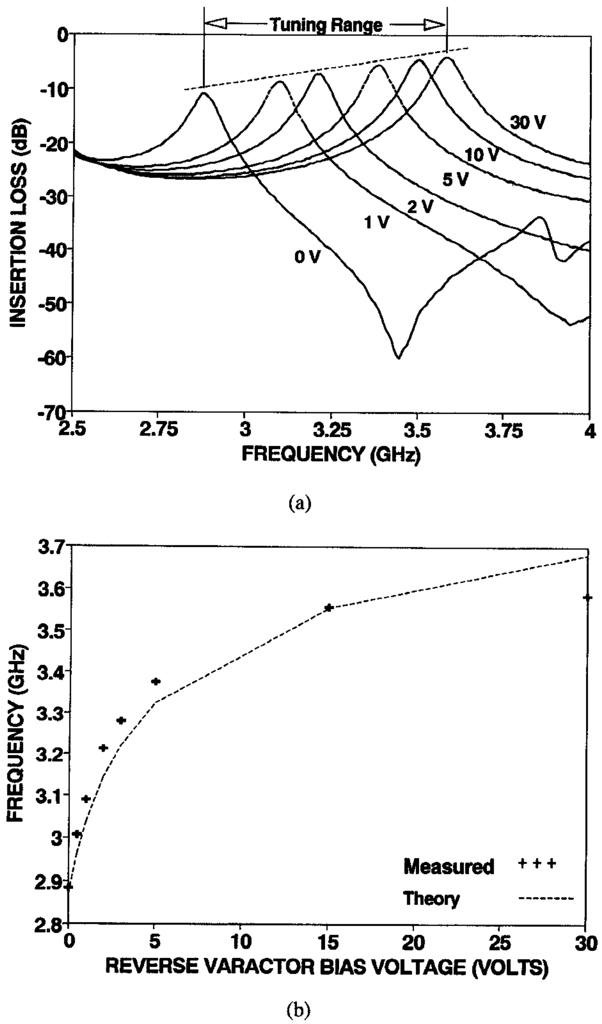

Fig. 15. Varactor tuning of the second resonant mode of a CPW ring resonator (a) Measured insertion loss for different varactor voltages. (b) Theoretical versus measured second resonant mode frequency as a function of varactor voltage.

input/output coupling. The loss increases linearly from 4 dB at 3.59 GHz to 10.5 dB at 2.88 GHz. Although two varactors can be used at either point on the ring, only one was used for this investigation. The insertion loss of the CPW ring could be reduced by using the similar dielectric overlay at the input and output as was used in the slotline ring.

VII. Conclusions

Uniplanar slotline and CPW ring resonators have been developed to provide a useful electronic tuning range. The configurations can be easily designed to match, switch, or tune modes electronically. The circuit is uniplanar and allows series and shunt connections of solid-state devices. The designs can be fabricated using monolithic techniques without the need for via holes which should reduce processing complexity and improve yields. The circuits should have many applications in filtering, switching, stabilizing and signal processing.

Acknowledgment

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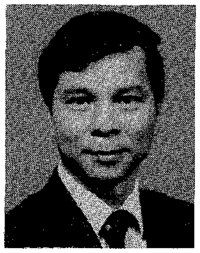

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