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Note: Tunable overlapping half-ring resonator

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A unique tunable microwave resonator with a pair of half-rings is introduced and validated by experimental data. The capacitive gap between the overlapping areas can be controlled accurately using a magnetic actuator for tunability. The design geometry is scalable to cover different bands of electromagnetic spectrum. Transmission characteristics of the resonators have been modeled using finite-element analysis and have been measured. The experimental results indicate the resonant frequency can be controlled with a resolution of a few MHz in a tuning range of 38%. The resonator exhibits sharp transmission dips within the tuning range with measured quality factors larger than 2500. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4825347]

Split ring resonator (SRR) structures have been employed effectively to define negative values of magnetic permeability since their introduction in the field of electromagnetic research in 1999.[1] Conventionally, a SRR is a thin planar metal loop on a dielectric substrate with a small split. Magnetic field perpendicular to a SRR structure induces magnetic resonance by supporting circulating current along the ring. The structure behaves as a diamagnetic material, hence exhibits negative values of magnetic permeability, above its magnetic resonant frequency. The resonant frequency can be tailored by changing the geometry of the structure. SRR structures in different geometries with resonant frequencies in microwave,[2,3] terahertz,[4] and visible frequencies[5] have been demonstrated. Metamaterials obtained by combining SRR structures with cut-wires exhibit both negative values of magnetic permeability and dielectric permittivity. Metamaterials have been introduced for various applications such as possessing negative index of refraction[6] and enhancing absorption.[7]

The resonant frequency of a ring resonator is determined by an equivalent inductance defined by the metal loop and an equivalent capacitance defined by the split and the surface of the metal loop.[8] These parameters are set by the geometry of the structure, yet reconfigurable devices are desirable to control the resonant frequency. Resonance characteristics of SRR structures exhibit a relatively high quality factor, leading a narrow spectral bandwidth. Capability of tuning the resonant frequency has been demonstrated by simply adding discreet capacitors to the SRR structures in microwave frequencies.[9] Additional capacitance decreases the resonant frequency effectively. However, the control in frequency is limited due to discrete values of additional capacitance. Recently, doped graphene has been coupled with SRR structures to develop tunable metamaterials by changing the conductivity of graphene.[10] The gap capacitance of SRR structures can also be altered using photodoping effect.[11] This effect has been proposed as optical modulator at microwave frequencies. Tuning the equivalent capacitance using an electrical control signal is also possible by loading SRR structures with varactors.[12,13] It is convenient to control the resonant frequency by electrical means. However, the quality factor of the resonator typically drops when the device is loaded by the equivalent capacitor, which is dominated by the varactor capacitance. The capacitance of the SRR structure can be altered at demand by changing the geometry of the device. Electrostatic comb-drive actuators have been employed to develop tunable metamaterials at terahertz frequencies,[14] but continuous change of resonant behavior is absent. In another study, thermal actuators are demonstrated to mechanically reconfigure a metamaterial structure by altering the coupling between two SRR structures.[15]

In this paper, we introduce a tunable microwave resonator using a pair of half rings. The rings are brought close to each other with an overlapping area. The distance between the rings is accurately controlled using a magnetic actuator for tunability. This capability essentially adds another knob to adjust the properties of overlapping half-ring resonators (OHR) on demand.

Fig. 1(a) shows a three-dimensional drawing of the OHR structure on an FR4 substrate. The OHR structures are designed in microwave frequencies and a pair of monopole antennas is defined on top of the substrate for experimental characterization. One of the half rings is on a movable cantilever anchored to the substrate as shown in Fig. 1(b). The cantilever moves against a stationary half-ring placed on top. The gap height between the half rings and the overlapping area define a tunable parallel plate capacitor.

Magnetic field perpendicular to the plane of OHR structure induces magnetic resonance at the resonant frequency, f_m:

$$f_m = \frac{1}{2\pi\sqrt{L_{eff}(C_s + C_{ov})}}, \qquad C_{ov} = \frac{\varepsilon_o A_{ov}}{g}, \qquad (1)$$

where ε_o is the permittivity of free space, L_{eff} is the effective inductance along the ring resonator, C_s is the surface capacitance, and C_{ov} is the capacitance associated by the overlapping area (A_{ov}) and the electro-mechanically controlled gap height (g). Surface capacitance takes the surface charges into account and the model of Ref. 8 is considered in our

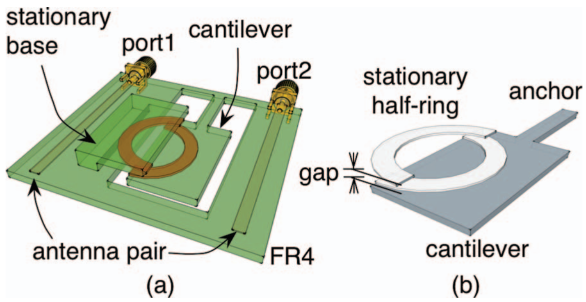

FIG. 1. Three-dimensional drawing of (a) an OHR structure and integrated monopole antennas on a dielectric substrate; (b) a movable half-ring on top of an anchored cantilever and a stationary half-ring are separated by a gap height.

calculations. Magnetic and kinetic inductances define the effective inductance.[8] The overlapping capacitance is a function of gap height and is used to control the resonant frequency of the OHR structure.

We designed OHR structures operating in the S-band on insulating substrate by using 35 μm thick copper. The inner and outer radii of a half-ring are 5 and 7 mm, respectively. The nominal gap height between the half-rings is 290 μm. Moving the rings in-plane towards each other by 2.58 mm forms the overlapping area. We simulated the electromagnetic behavior of OHR structures using a commercially available finite-element analysis (FEA) software (Ansys HFSS). FEA simulation indicates a magnetic resonance at 3.28 GHz for a gap of 290 μm. The frequency response of transmission characteristics of the model is shown in Fig. 2. Increasing the gap height shifts the resonant frequency to higher values due to decreased overlapping capacitance. The tuning mechanism is bidirectional, hence decreasing the gap height simply reduces the resonant frequency.

We fabricated the designed OHR structures and monopole antennas on a 1.57 mm thick FR-4 copper-clad laminate. The stationary half ring is rigidly attached on top of the substrate with a predetermined gap height between the half rings. A permanent magnet is attached at the backside of the cantilever for magnetic actuation. The cantilever can be actuated using another permanent magnet on a micromanipulator brought within the vicinity of the cantilever. The deflection of the cantilever, hence the change in gap height, is

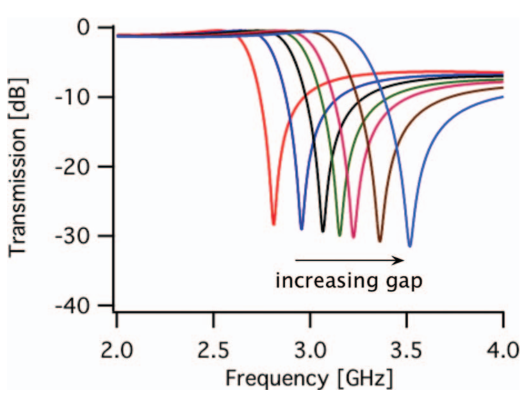

FIG. 2. FEA simulations showing transmission spectra of the OHR structure with varying gap heights.

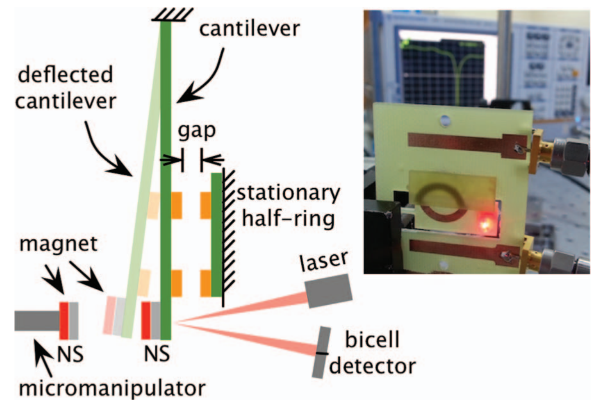

FIG. 3. Schematics of the experimental setup. Inset to the figure shows the photograph of the experimental setup.

measured using an optical lever readout method as schematically shown in Fig. 3. Optical lever is a sensitive method, which is commonly used in atomic force microscopy.[16] We actuated the cantilever while recording the frequency response of transmission characteristics and the gap height. We obtained the transmission characteristics by measuring s_{21} scattering parameter of the device, inserted between the impedance-matched monopole antenna pair, using a vector network analyzer (ZVB4, Rohde&Schwarz, Munich, Germany).

Fig. 4(a) shows the transmission spectra of the OHR corresponding to different gap heights adjusted by the actuator. The resonant frequency of the OHR with a nominal gap of

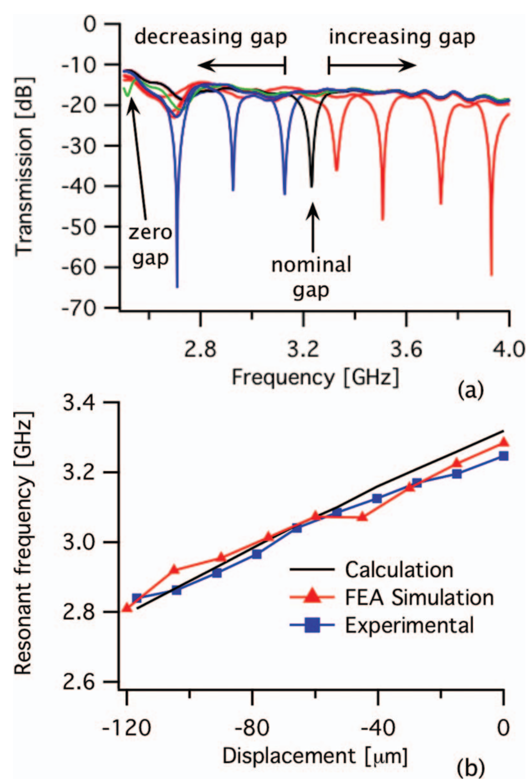

FIG. 4. (a) Measured transmission spectra of the OHR structure with varying gap heights. (b) Shift in resonant frequency of the OHR structure with respect to displacement of the cantilever.

290 μm is 3.25 GHz. The resonant frequency of the device can be reduced to 2.5 GHz before the cantilever makes contact with the stationary half ring. At the contact we do not observe resonance as expected. On the other hand, increasing the gap height can increase the resonant frequency of the device to 3.93 GHz as shown in Fig. 4(a). Hence experimentally verified modulation range of the tunable OHR is extracted to be 38%.

Dependency of resonant frequency on the displacement of the cantilever is shown in Fig. 4(b). Negative displacement values indicate reduction in gap height. There is good agreement between experimental values, FEA simulations, and calculations of Eq. (1). Displacement range presented here corresponds to the linear detection range of the optical lever readout mechanism used for our experiments. The resonant frequency of the OHR can be controlled with a sensitivity of 3.7 MHz/μm. The displacement of the cantilever can be controlled with micrometer resolution and the travel range is limited by the initial gap. Experimental data show that it is feasible to tune the resonator with a resolution of a few MHz in a band of a few GHz.

The resonator exhibits sharp transmission dips within the tuning range. Quality factors in excess of several thousands are experimentally observed. The bidirectional actuator does not have detrimental effect on the quality factor. Thus, the performance of the device is not degraded within the entire tuning range.

In summary, overlapping half-ring resonator structure is introduced. A method of tuning the resonator characteristics has been demonstrated. Current OHR structures are developed in the S-band and it is feasible to scale the geometry of the structure to design resonators in different bands of electromagnetic spectrum. The resonant frequency of the devices can be controlled with MHz resolution in 2.5–4 GHz using a magnetic actuator.

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