

Si layer of Al layer of
 Lcant cantilever
 glass substrate
^{4 6}
 G n ε

Fig. 1. Dimensions of a) split ring resonators without cantilever, and b) cross section view of cantilever with anchor implemented over the split gap of the inner ring.

SRRs were first theoretically proposed by Pendry et al. [6] and have attracted growing interests since. Many variations of SRRs have been proposed, mainly to realize a negative magnetic permeability material in a time-varying H-field component of a perpendicularly polarized wave incident on its surface. The metamaterial medium consisting of SRRs was shown to be highly frequency selective, suggesting the SRR elements have very high quality factor ($Q \approx 600$) [7-8]. When the SRRs are excited, the slits on each ring force the current to flow from one ring to another across the slot between them, which behaves effectively as a distributed capacitance. Thus, the field at the slit on each ring is highly concentrated, suggesting that by modifying the capacitance of these slots, the current on the rings is strongly influenced, and therefore, the resonant frequencies are shifted significantly. In our design, the Al layer of the cantilever is the lower layer of the bimorph cantilever and is shorted to one side of the split gap on the inner ring through the anchor, which is also made of Al. Thus, the deflection at the end of this cantilever effectively modifies the split gap capacitance. On the other hand, micro-cantilevers have been widely utilized in MEMS for various sensing applications. A bimorph cantilever consists of a metal and a dielectric, which is commonly fabricated in MEMS. Each material has a different thermal expansive coefficient, as the temperature changes their lengths change at different rate, thus causes the bimorph cantilever to bend [9]. Such a deflection (when implemented at the splits of SRRs) forms an ultrasensitive temperature sensor, and when based on MEMS, they are also robust, easily fabricated, and can be produced in high yield. It should be noted that the temperature sensing of the transducer is based on two uncoupled principles: 1) the deflection of the bimorph cantilevers in response to the temperature change, and 2) the resonant frequency shifts in response to the deflection of the cantilevers. The operation of the first principle is well-known and has been utilized widely in numerous applications [1- 4, 9]. Thus, our simulations and proof-of-concept prototype are presented to mainly demonstrate the operation of the second principle in which the resonant frequency is shifted as a response to the cantilevers' deflection. Furthermore, at any given operating frequencies, the choice of materials is the factor that determines the upper and lower limit of temperature sensing range, rendering the design a highly broad applicability.

III. $5G3^M L87DM^7M F59.B^EGB.M IBDGDM/B.AG.7\alpha IM$
 $B.D987D.M 8_1/ME1.M5,33,5.E.BM 1^1.M FB^7D,G\alpha.BM ,D_107M$

The deflection of the micro-cantilevers is approximated in simulations with a uniform deflection across the whole structure of cantilevers. A plane wave is incident on the infinite glass slab that supports the SRRs with a micro bimorph cantilever. The model is simulated in a 2-port set up in CST Microwave Studio 2009. In this model, only one

cantilever is implemented, placed over the inner ring split. The S-parameters of two different h values (3 μm and 5 μm) are shown in Fig. 2, representing two different temperature states of the cantilever. The two resonances are observed at 29.87 GHz and 31.96 GHz showing a frequency shift of 2.09 GHz over 2 μm difference in cantilever height. Hence, the sensitivity is 1.05 GHz/ μm with respect to the cantilever's deflection. Eq. 1 [9] is used to estimate the deflection of the cantilever whose parameters given in Sect. II, thus yields a sensitivity of 0.143 $\mu m/^\circ C$ in terms of deflection versus temperature. Therefore the sensitivity of the temperature sensor is approximately 150 MHz/ $^\circ C$, three orders of magnitude higher than previously reported [4][5]. In equation (1), d is the deflection of the free end, L is the length of the cantilever, α_1 and α_2 are the coefficients of thermal expansion of the low and high expansive material respectively, n is the ratio of E_1/E_2 which are the Young's moduli of low and high expansive materials respectively, m is the ratio of t_1/t_2 with t_1 and t_2 their respective thicknesses, and t is the total thickness of the cantilever.

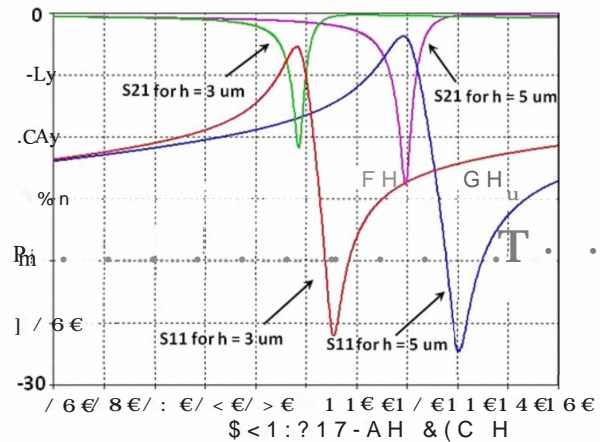


Fig. 2. S11 and S21 of the passive temperature transducer based on SRRs and a bimorph cantilever.

IV. $D_107/M 1^1/(B,\alpha^M L87D/M^7M 6^1DGB5.7EDM 8_1/ME1.M$
 $FB^7D,G\alpha.BM ^\alpha^4,M :B8E8E19.DM ^B8H7,M 4 GHz B^70.M$

Desi g m d F a b r i c a t i o n t s i l e v e r s
p r o t o t y p e s n R R t e m p e r a t u r e
m o d e p e r a n o i n g d

Two scaled model of the design proposed in Sect. III are fabricated. The first one is fabricated on Neltec N9217 substrate ($\epsilon_r 2.17$, substrate thickness = 787 μm). The dimensions of the SRRs in this model are as follows: r_{int}

