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RESEARCH ARTICLE

Wide frequency switchable microwave resonator by injecting eutectic gallium indium into microfluidic defected ground structure

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Abstract
This article proposes a frequency switchable microwave resonator based on a microfluidic defected ground structure (m-DGS) that provides wider frequency tuning ratio. Because its resonant frequency is determined from the DGS geometry, the resonant frequency can be switched by injecting EGaIn liquid metal into the m-DGS to decrease the effective inductance and hence increase resonant frequency to 7.7 GHz from 3 GHz, that is, 88% tuning range. The proposed idea is demonstrated numerically and experimentally.

KEYWORDS
defected ground structure, frequency switching, liquid metal, microfluidic channel, resonator

1 | INTRODUCTION

Defected ground structures (DGSs) have been used previously for compact microwave resonators because inductive/capacitive (LC) resonance can be generated from the slot on the ground plane of the transmission line, and hence, additional space is not required.[1] The narrow and wide etched regions on the bottom ground plane can enhance effective inductance and capacitance, respectively. DGS resonators have also been used for various microwave applications, such as low-pass filters, band-pass filters, band-stop filters, antennas, and sensors.[2–6] Various configurations and devices have been proposed to provide multi-functionality or tunable DGS based microwave circuits. For example, a tunable band-stop DGS resonator was proposed by loading varactor diodes on the dumbbell shaped defected ground of the co-planar waveguide (CPW), achieving 19% tuning range.[7] A tunable band-pass filter was proposed by loading varactor diodes and capacitors on the octagonal DGS, achieving 22.7% tuning range.[8] A tunable band-pass filter was proposed using micro-electric mechanical system (MEMS) series resistive switches between the stub and ground plane,[9] and a tunable band-stop filter was proposed using DGS and MEMS switches, achieving 36.5% tuning range.[10] A compact tunable band-pass filter using T-DGS and ceramic capacitor, achieving 47% tuning range.[11] A tunable WLAN-band-pass filter using varactor device, achieving 23.3% tuning range.[12]

This article proposes a wide frequency switchable microfluidic DGS (m-DGS). Because the DGS resonant frequency can be determined from the DGS geometry, resonant frequency switching can be achieved by injecting eutectic gallium indium (EGaIn) liquid metal into the m-DGS to effectively decrease inductance, hence increasing resonant frequency to 7.7 GHz from 3 GHz, that is, 88% tuning range. The proposed concept is numerically and experimentally demonstrated.

2 | DESIGN AND ANALYSIS OF THE M-DGS RESONATOR

Figure 1a and b shows the layout and equivalent LC circuit model, respectively, for a primitive DGS resonator. The small microstrip line gap corresponds to the effective capacitance, and the wide ground plane slot corresponds to the effective inductance. Therefore, resonance frequency is dependent on the LC resonator geometry of this LC resonator. Figure 1c and d shows the proposed m-DGS to switch resonance frequency. Two microfluidic channels are loaded on each slot of the

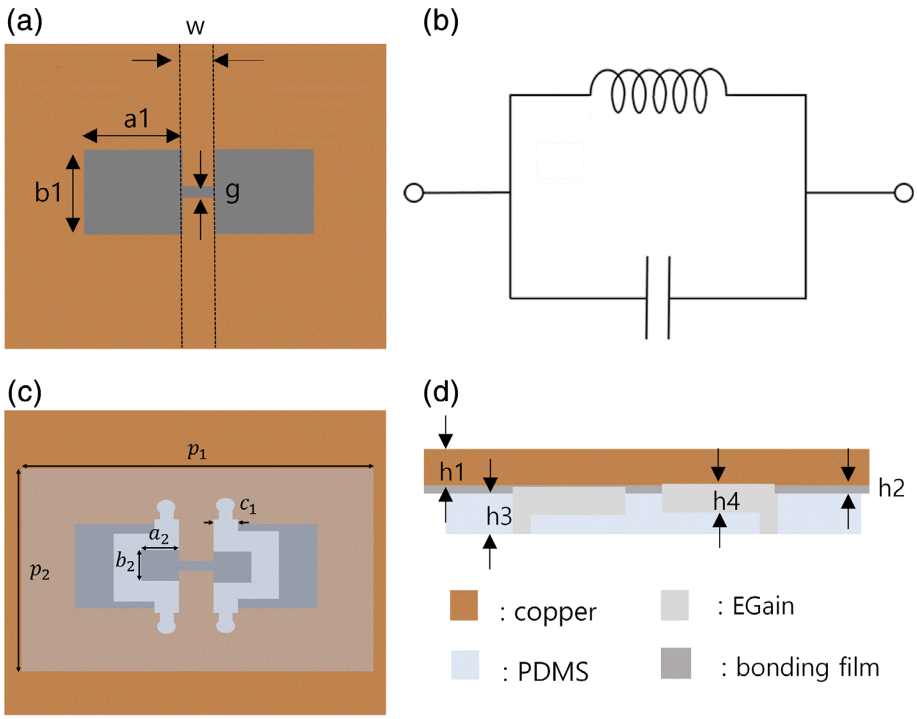

FIGURE 1 (a) Primitive dumbbell shaped DGS resonators and (b) the equivalent LC circuit model; (c) bottom and (d) side views of the of the proposed m-DGS [Color figure can be viewed at wileyonlinelibrary.com]

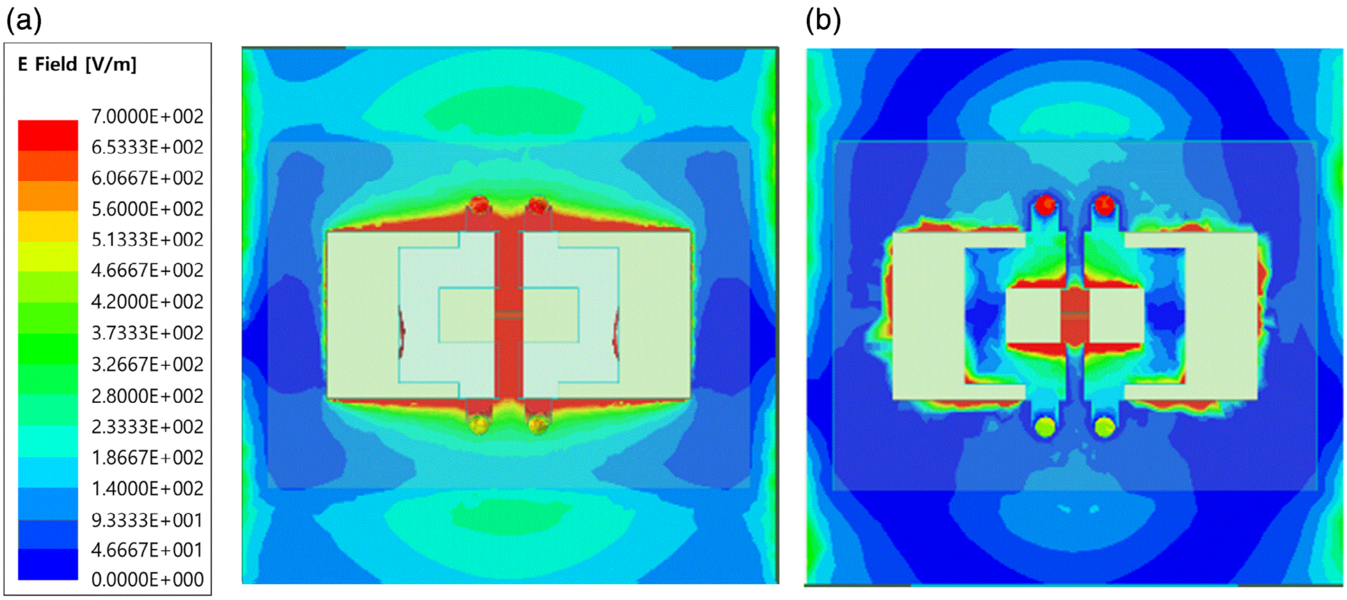

FIGURE 2 Electric field distribution for the m-DGS resonator (a) without and (b) with liquid metal (3.3 and 8.1 GHz resonance, respectively) [Color figure can be viewed at wileyonlinelibrary.com]

ground plane to allow changing the effective inductance. When the liquid metal is injected into the microfluidic channel, the effective inductance will decrease, thereby increasing the resonance frequency.

The DGS was built on 0.78 mm thick Rogers RT/duroid 5870 substrate with dielectric constant and tangential loss 2.33 and 0.0012, respectively. The microfluidic channel was built from the polydimenthysiloxane (PDMS) material, and it had dielectric constant and tangential loss 3 and 0.02, respectively. Two substrates were combined by using the bonding film, which had dielectric constant and tangential loss = 3 and 0.05, respectively. The conductivity of liquid metal is 3.4×10^6 S/m.

We used the ANSYS high frequency structure simulator (HFSS) to design the proposed m-DGS resonator, with geometry (Figure 1) final geometry: $a_2 = b_2 = 4.1$, $c_1 = 3$,

$p_1 = 36$, $p_2 = 26$, $h_1 = 0.78$, $h_2 = 0.05$, $h_3 = 1$, and $h_4 = 0.85$ (all parameters are millimeters).

Figure 2 shows the simulated electric field magnitude of the proposed m-DGS resonator. The m-DGS without liquid metal initially resonates at 3.3 GHz, and the microfluidic channel does not contribute to this resonance. When liquid metal is injected into the microfluidic channel, the m-DGS resonates at 8.1 GHz. Figure 2b shows that the etched region on the ground plane becomes smaller, effectively reducing inductance.

3 | FABRICATION AND MEASUREMENT

To demonstrate the proposed concept, we designed and fabricated a typical m-DGS resonator, as shown in Figure 3. The top view (Figure 3a) shows the 50-Ω microstrip line fabricated on top of the Rogers RT/duroid 5870 substrate. Figure 3b and c shows bottom views without and with liquid metal, respectively. Dumbbell shaped slots were etched onto the Rogers substrate and microfluidic channels built on the PDMS, respectively. The microfluidic channels were constructed by laser etching. EGaIn was used as the liquid metal because it has lower toxicity and significantly less maintenance than mercury.

Figure 4a shows the simulated return loss (S_{11}) of m-DGS with liquid metal at different length of the microfluidic channel (a_2). It is observed that the resonant frequency is decreased from 13 to 6 GHz by increasing a_2 from 1.1 to 7.1 mm. It is because larger a_2 corresponds to a larger slot size of the DGS and larger inductance. Figure 4b shows the simulated S_{11} of m-DGS with liquid metal at different width

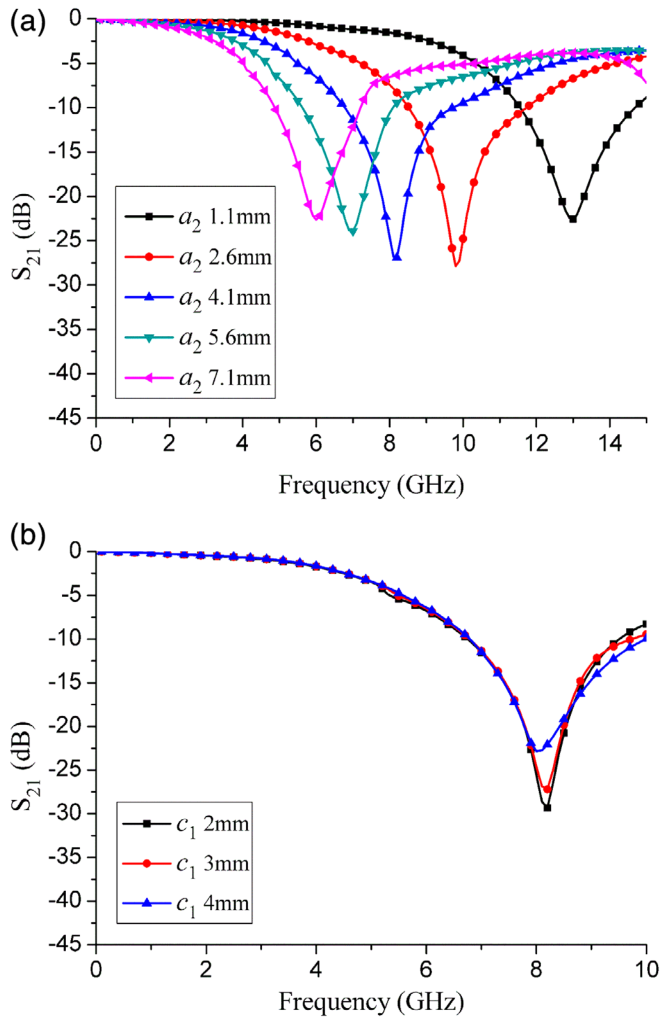

FIGURE 4 Simulated return loss of m-DGS with liquid metal at (a) different a_2 and (b) c_1 [Color figure can be viewed at wileyonlinelibrary.com]

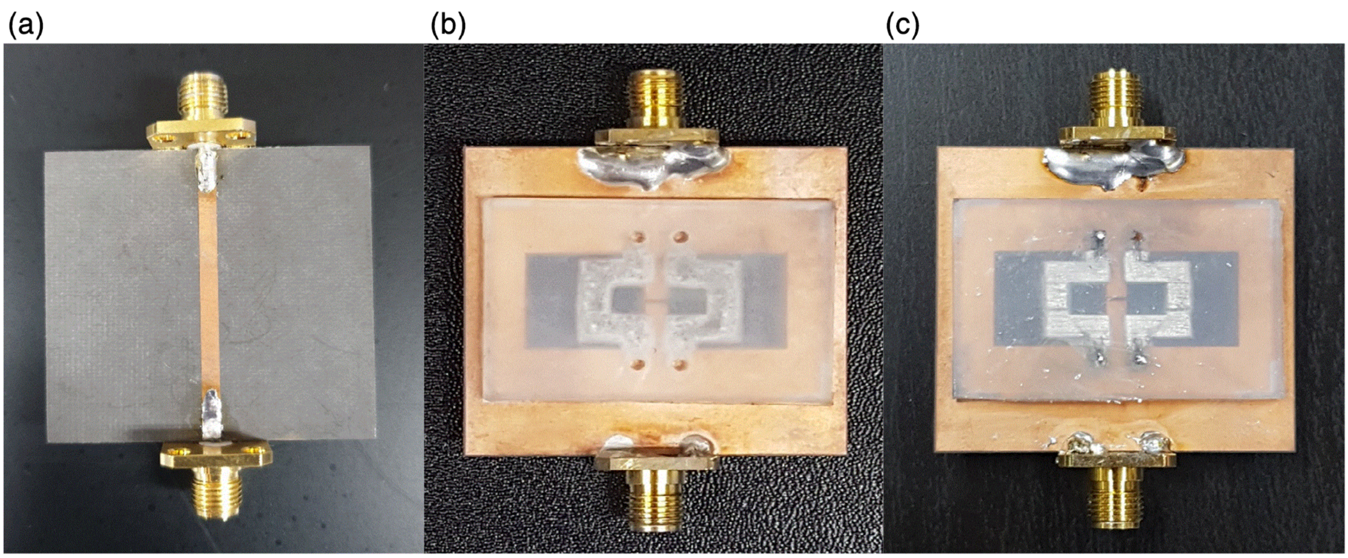

FIGURE 3 Picture of the fabricated m-DGS resonator (a) top, and bottom (b) without and (c) with EGaIn liquid metal [Color figure can be viewed at wileyonlinelibrary.com]

of the microfluidic channel (c_1). It is observed that the resonant frequency is almost not changed and the amplitude is slightly changed although c_1 is varied. Therefore, we choose $c_1 = 3$ mm after considering reliable fabrication, minimum amount of liquid metal, and smooth flow of liquid metal.

To see the effect of PDMS and bonding film, the proposed m-DGS resonator without liquid metal is simulated. Figure 5a and b shows the simulated insertion loss (S_{21}) and return loss (S_{11}) of the m-DGS without liquid metal, respectively. It is observed from Figure 5 that the resonant frequency is decreased from 4.1 to 3.3 GHz after loading PDMS on the resonator. It is because dielectric constant of PDMS is higher than dielectric constant of RT/duroid substrate. However, the bonding film does not affect S parameter because of its thin thickness.

Figure 6a shows the proposed m-DGS resonator simulated S parameters. Resonant frequency without EGaIn = 3.3 GHz with −22 dB S_{21}, which increased to 8.1 GHz with −26 dB S_{21}. Figure 6b shows the measured S-parameters of the

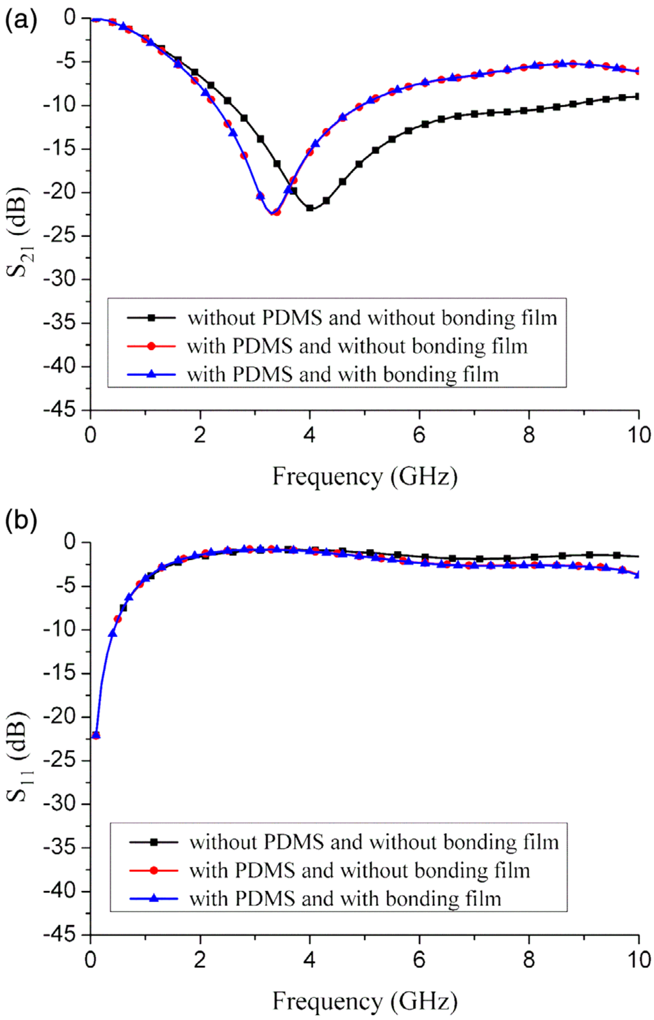

FIGURE 5 Simulated S parameters of m-DGS without liquid metal to see the effect of the PDMS and bonding film: (a) insertion loss and (b) return loss [Color figure can be viewed at wileyonlinelibrary.com]

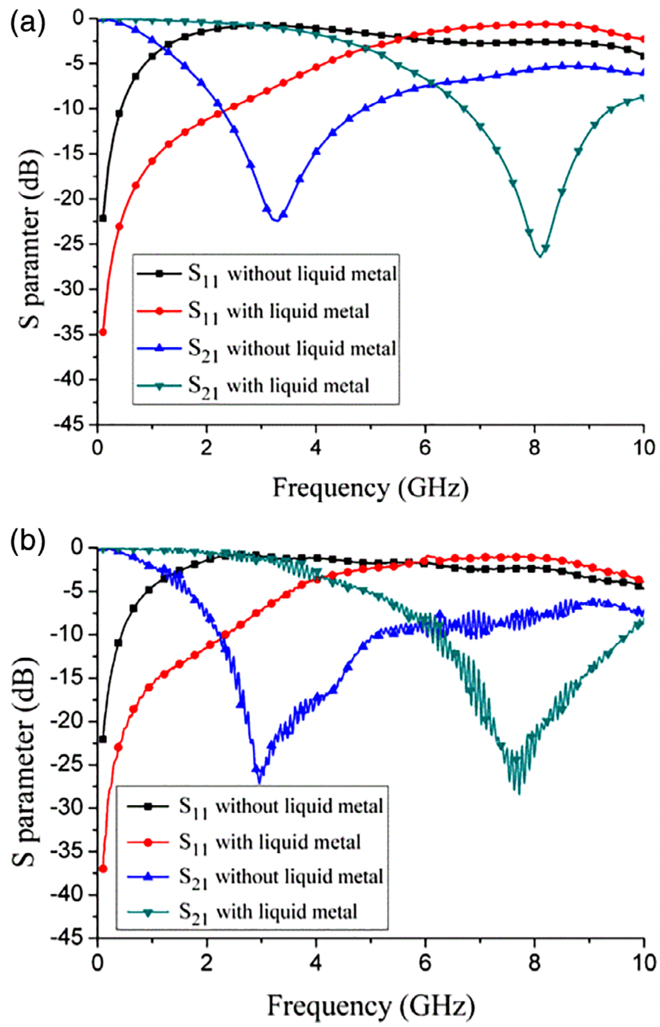

FIGURE 6 (a) Simulated and (b) measured S parameters of the proposed m-DGS resonator [Color figure can be viewed at wileyonlinelibrary.com]

proposed m-DGS resonator. Before injecting EGaIn into the microfluidic channel, resonant frequency is 3 GHz with −26 dB S_{21}. When EGaIn is injected, resonant frequency is increased to 7.7 GHz with −28 dB S_{21}. The slight frequency difference is due to fabrication error in the microfluidic channels and PDMS misalignment.

The tuning range can be expressed as

$$\frac{f_1 - f_2}{f_0} \times 100(\%) \tag{1}$$

where f_1, f_2, and f_0 are the highest and lowest resonant frequencies and center frequency, respectively. Therefore, the proposed m-DGS resonator measured tuning ratio = 88%. In Table 1, the performance of the proposed DGS resonator is compared with that of other tunable DGS resonators. The proposed resonator shows widest tuning range due to fluidic switching mechanism. In addition, the insertion loss of the proposed resonator is also lower than electrically tunable resonators because of parasitic resistance from electronic devices.

TABLE 1 Performance comparison of the proposed tunable DGS resonators with other tunable DGS resonators

	Tuning range (%)	Lowest Freq. (GHz)	Highest Freq. (GHz)	*S*-parameters at lowest Freq. (dB)		*S*-parameters at highest Freq. (dB)		Tuning mechanism
				S_{11}	S_{21}	S_{11}	S_{21}	
7	19	3.35/6.7	4.05/8.1	3[a]/2[a]	12.5[a]/19[a]	2[a]/2[a]	23[a]/24[a]	Varactor diode
8	22.7	4.3	5.4	15[a]	5	20[a]	3	Varactor diode
10	36.5	8.5	12.3	2.8	18[a]	2.3	24[a]	MEMS
11	47	1.3	2.1	23[a]	0.5[a]	30[a]	0.5[a]	Ceramic capacitor
12	23.3	2.87	3.63	20[a]	3.6	18[a]	2.1	Varactor device
Proposed work	88	3	7.7	0.85	26	0.97	28	Fluidic (Liquid metal)

[a] It is estimated from the graph.

4 | CONCLUSION

This article proposed a frequency switchable m-DGS resonator, and we demonstrated its performance numerically and experimentally. The proposed resonator resonance frequency increased from 3 to 7.7 GHz by injecting EGaIn liquid metal into the microfluidic channels. Thus, 88% frequency tuning ratio was successfully achieved by modifying DGS conductive patterns using the liquid metal. Therefore, the proposed m-DGS resonator could be suitable for microwave filters with wide tuning capability.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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