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Phase Coherence Method for the Resonant Frequency Analysis of the Modified Dumbbell-Shaped Defected Ground Structure Resonator on Coplanar Waveguide*

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Abstract — A The resonance of the Modified dumbbell-shaped defected ground structure (MD-DGS) resonator on coplanar waveguide is investigated systematically based on the phase coherence of electromagnetic waves. Through the analysis of two presented interference modes, the resonant frequencies can be fully predicted, and the physical understanding behind these resonances is clearly revealed. The proposed analysis is verified by the simulation and measurement results of the MD-DGS resonator. Both the electric field distribution and the Poynting vector distribution of the MD-DGS resonator at the resonant frequencies further demonstrate the validity of the theoretical analysis.

Key words — Phase coherence, Resonant frequency, Defected ground structure.

I. Introduction

Defected ground structure (DGS) has provided a popular solution for many microwave applications and various kinds of DGS resonators have been proposed to achieve a higher performance[1−4]. Recently, much research has been concentrated on the Modified dumbbell-shaped DGS (MD-DGS) resonator on Coplanar waveguide (CPW)[5−8]. This is because the structure is simple and easy in design, meanwhile, the CPW technology can facilitate the shunt connection to ground and integrate with active devices. However, most of the work has explained the resonances by means of the equivalent RLC circuit method without providing the design rules. An explanation to the resonant frequencies of the MD-DGS resonator is obtained from the perspective of Electromagnetic wave (EM) propagation in Ref.[6]. Nevertheless, the comprehensive analysis of the resonances of the MD-DGS resonator needs to be further investigated.

Interference of EM waves is the combination of separate EM wave in the same space. When the resultant wave exhibits the amplitude greater or less than that of individual wave, constructive or destructive interference occurs. Thus, the resonance may be regarded as the constructive and destructive interference[9,10] while the phase coherence is the essential cause. The analysis of the resonance using the phase coherence will give more definite physical understanding compared with the equivalent circuit method.

This paper presents the systematic analysis of the resonant frequencies of the MD-DGS resonator based on the phase coherence method. Firstly, two interference modes of the MD-DGS resonator are presented to obtain the formulas for the resonance prediction. Secondly, the MD-DGS resonator is simulated and measured to verify the proposed analysis. The simulations of the MD-DGS resonators with different dimensions are conducted. The electric field distribution and the Poynting vector distribution at the resonant frequencies are also provided.

II. Phase Coherence Method for the Resonant Frequency Analysis of the MD-DGS Resonator

It is well known that when the phase difference of two waves is even multiple of, the constructive interference occurs; when the phase difference is odd multiple of , the destructive interference occurs. According to this, the resonant states of the MD-DGS resonator may be produced from two ways shown in Fig.1. On one hand, the EM waves with propagation path (1) and path (2), denoted by the red solid line and the blue dashed line in Fig.1(a) respectively, may interfere destructively with each other at point "P" when the phase difference is satisfied. The condition of this destructive interference mode can be written as follows:

$$2\pi \cdot d_1/\lambda_{gr} = (2n+1)\pi, n = 0,1,2,\cdots \qquad (1)$$

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where $d_1 = 4a + 2d$ is the path difference between path (1) and path (2), λ_{gr} is the slotline wavelength at the resonant frequency.

On the other hand, apart from the EM wave propagation path (1) and path (2), another propagation path (3) may exist simultaneously, which is denoted by the blue dotted line in Fig. 1(b). When the phase difference along the square resonator is even multiple of , the EM waves interfere constructively. The expression of this constructive interference mode may be obtained as:

$$2\pi \cdot d_2/\lambda_{gr} = 2n\pi, n = 0, 1, 2, \cdots \quad (2)$$

where $d_2 = 4a - 4w$ is the average circumference of the square resonator.

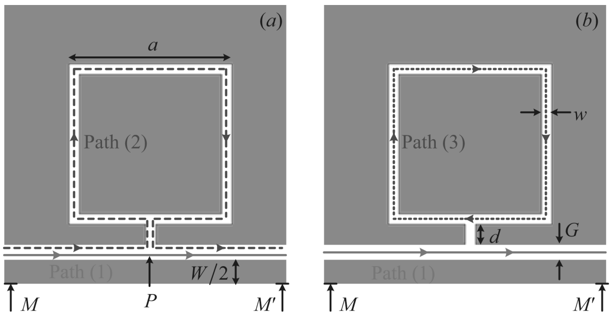

Fig. 1. Schematic diagram of the resonant states analysis of the MD-DGS resonator (half symmetrical view). (a) Destructive interference mode at point "P". (b) Constructive interference mode along the square resonator

The relationship between the slotline wavelength λ_{gr} and the free space wavelength λ_0 can be determined by the closed form expressions in Ref.[11]. For the substrate with dielectric constant $\varepsilon_r = 11.8$ and thickness $h = 0.8$ mmused in our case, this relationship is described as:

$$\begin{aligned}\lambda_{gr}/\lambda_0 = 0.987 - 0.483 \log(\varepsilon_r) + w/h\,(0.111 - 0.0022\varepsilon_r) \\ - (0.121 + 0.094w/h - 0.0032\varepsilon_r) \log\left(h/\lambda_0 \times 10^2\right)\end{aligned} \quad (3)$$

Note that using the Eqs.(1), (2) and (3), the transmission zeros of the MD-DGS resonator can be fully predicted prior to any circuit or full-wave simulation, making the design process more efficient.

III. Method Verification and Discussion

The MD-DGS resonator with a =8 mm, d =1 mm, and the CPW parameters $G/W/G = 0.8/3/0.8$ mm is simulated using the full-wave EM solver ansoft High frequency structure simulation (HFSS). The fabricated structure shown in Fig.2 is measured to testify the simulated results. Fig.3 shows the simulated and measured transmission coefficients of the MD-DGS resonator, where a good agreement between the simulation and measurement is obtained. The discrepancy in the resonant frequency and the insertion loss at the higher frequency range may be resulted from the tolerance in manufacturing, the effects of the SMA connectors in the measurement, and the imperfect characteristics of the employed dielectric substrate.

Five resonant frequencies can be predicted for the fabricated M-DGS resonator in the frequency band up to 11 GHz and they are listed in the second column of Table 1. The first, third and fifth resonances correspond to the destructive interference mode at point "P", while the second and fourth resonances correspond to the constructive interference mode along the square resonator. We could find that the predicted resonances agree well with the actual resonances. The relative errors representing the ratio of the absolute frequency difference between the predicted resonance and the actual resonance to the actual resonance are all below 3.5%.

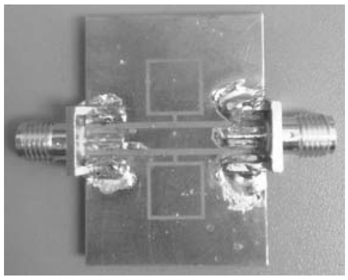

Fig. 2. Photograph of the fabricated MD-DGS resonator

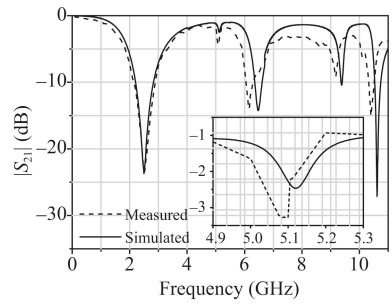

Fig. 3. Simulated and measured transmission coefficients of the MD-DGS resonator

To further investigate the resonance, the MD-DGS resonators with different a and d are simulated. The predicted and the simulated resonances are listed in Table 1 and Table 2 respectively, where good agreements between the two can be clearly observed. From Table 1 and Table 2, we could also find that: when d is fixed at 1 mm, the resonant frequency corresponding to the two interference modes both decreases as a increases. This is due to that the path difference d_1 and d_2 both increase in this case. When a is fixed at 8 mm, the resonant frequency corresponding to the destructive interference mode decreases as d increases, while the resonant frequency corresponding to the constructive interference mode almost remains invariant. This can be explained with that when d increases, the path difference d_1 increases while the path difference d_2 is not varied.

Fig.4 shows the electric field distribution of the fabri-

Table 1. Resonant Frequency Analysis of the MD-DGS Resonator with Different a

Resonance	$a = 8$ mm, $d = 1$ mm			$a = 9$ mm, $d = 1$ mm			$a = 10$ mm, $d = 1$ mm		
	Predicted (GHz)	Actual (GHz)	Error (%)	Predicted (GHz)	Actual (GHz)	Error (%)	Predicted (GHz)	Actual (GHz)	Error (%)
1	2.45	2.50	**2.00**	2.21	2.26	**2.21**	2.02	2.05	**1.46**
2	5.09	5.10	**0.20**	4.55	4.60	**1.09**	4.12	4.14	**0.48**
3	6.52	6.48	**0.62**	5.91	5.81	**1.72**	5.41	5.29	**2.27**
4	9.40	9.39	**0.11**	8.42	8.50	**0.94**	7.63	7.70	**0.91**
5	10.25	10.62	**3.48**	9.29	9.47	**1.90**	8.51	8.57	**0.70**

Table 2. Resonant Frequency Analysis of the MD-DGS Resonator with Different d

Resonance	$a = 8$ mm, $d = 1$ mm			$a = 9$ mm, $d = 1$ mm			$a = 10$ mm, $d = 1$ mm		
	Predicted (GHz)	Actual (GHz)	Error (%)	Predicted (GHz)	Actual (GHz)	Error (%)	Predicted (GHz)	Actual (GHz)	Error (%)
1	2.39	2.39	**0.00**	2.32	2.27	**2.20**	2.27	2.16	**5.09**
2	5.09	5.13	**0.78**	5.09	5.21	**2.12**	5.09	5.16	**1.36**
3	6.37	6.35	**0.32**	6.20	6.22	**0.32**	6.05	6.11	**0.98**
4	9.40	9.50	**1.05**	9.40	9.50	**1.05**	9.40	9.51	**1.16**
5	9.99	10.52	**5.04**	9.75	10.40	**6.25**	9.51	10.28	**7.49**

cated MD-DGS resonator at the five resonant frequencies. There is one minimum, three minima and five minima along path (2) in Fig. 4(a), Fig. 4(b) and Fig. 4(c) respectively, which will cause 180°, 540° and 900° phase difference at point "P". Thus, the destructive interference should happen at this point. Two minima and four minima can be observed in Fig. 4(d) and Fig. 4(e) separately, resulting to 360° and 720° phase difference along path (3). This will produce the constructive interference along the square resonator. Therefore, the analysis of the two interference modes is further validated.

The Poynting vector distribution at the resonant frequencies is also provided as shown in Fig. 5 to give a better understanding of the resonances. In Fig.5(a), Fig.5(b) and Fig.5(c), a large amount of power flows into the DGS resonator and little power is transmitted to the output port for the destructive interference mode. While in Fig.5(d) and Fig.5(e), some power flows along the square resonator for the constructive interference mode. Therefore, the difference of the two interference modes is demonstrated. It is worth mentioning that there is some power transmitted to the output port at the resonances corresponding to the constructive interference mode, making the resonances not obvious as the destructive interference mode, especially for the second resonance in the aforementioned analysis, which may be observed in Fig.3. Except for that, the constructive interference mode still exists and cannot be neglected.

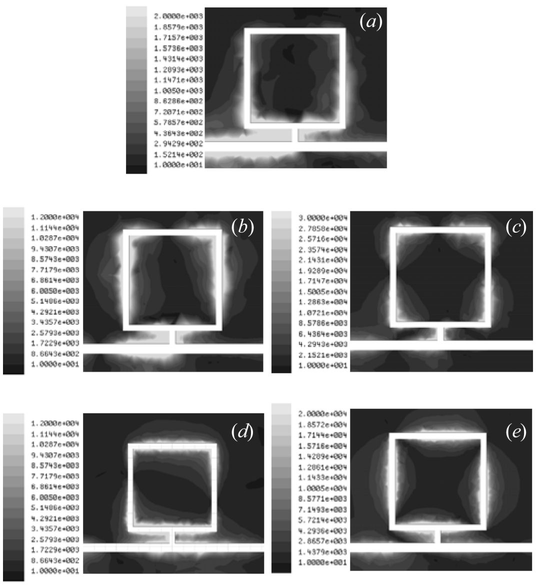

Fig. 4. Electrical field distribution of the MD-DGS resonator at the resonant frequencies (a) 2.50 GHz, (b) 6.48 GHz, (c) 10.62 GHz, (d) 5.10 GHz and (e) 9.39 GHz (half symmetrical view, unit: V/m)

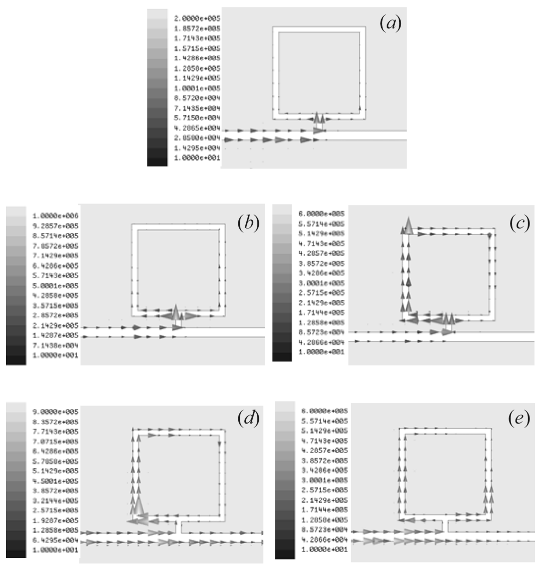

Fig. 5. Poynting vector distribution of the MD-DGS resonator at the resonant frequencies (a) 2.50 GHz, (b) 6.48 GHz, (c) 10.62 GHz, (d) 5.10 GHz and (e) 9.39 GHz (half symmetrical view, unit: W/m^2)

IV. Conclusion

The resonant frequencies of the MD-DGS resonator is analyzed comprehensively by mans of the phase coherence method. The expressions of the resonance condition are obtained through the analysis of the constructive and destructive interference modes. Simulation and measurement results of the fabricated MD-DGS resonator verify the proposed analysis. Through the simulations of the MD-DGS resonator with different dimensions, the electrical field and the Poynting vector distribution at the resonant frequencies, the validity of the theoretical analysis is further demonstrated. The proposed analysis method will greatly reduce the simulation time and computer memory for the design of the MD-DGS resonator.

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