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HIGHLY SELECTIVE SUSPENDED STRIPLINE DUAL-MODE FILTER

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Abstract—Miniature bandpass filter constructions based on a novel dual-mode suspended stripline resonator are proposed. Because of a special structure of the resonator, the frequencies of two first oscillation modes may be brought closer together. That allows realizing narrowband filters with the wide upper stopband. The filters have low insertion loss in the passband at small dimensions. Several transmission zeros substantially improve the filter performance. The derived coupling coefficients account for some features in the frequency response of the filter. The second-order and fourth-order filters with transmission zeros have been fabricated and measured.

1. INTRODUCTION

In modern wireless communication systems, compact bandpass filters with low insertion loss, wide upper stopband, and finite transmission zeros are in great demand. It is known that suspended stripline structures differ from other planar microwave structures in low current densities on the metallization. This results in low insertion loss in the passband. Suspended stripline bandpass filters, comprising capacitively coupled quasi-lumped resonators on both substrate sides, have a small size and wide upper stopband [1–3]. A dual-mode version of such broadband filters is described in [4]. The use of a mixed inductive-capacitive inter-resonator coupling enables to generate a transmission zero near the passband and to adjust its frequency [5].

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The suspended stripline filter has a smaller size when a capacitive segment of each quasi-lumped resonator consists of two strip conductors on opposite sides of the substrate and both inductive segments are grounded. The resonant properties of the resonator were studied analytically within a 1D model in [6]. The experimental characteristics of the bandpass filter were presented in [7]. Transmission zeros below and above the passband of the filter can be created by inserting a two-end grounded strip conductor between the adjacent resonators [8].

A bandpass monolithic planar filter using similar quasi-lumped resonators was described and manufactured in [9].

Thus, there is the challenge of designing compact highly selective narrowband filters with the wide upper stopband and low insertion loss in the passband.

In this paper, we propose a novel dual-mode suspended stripline resonator that is good for design of compact highly selective narrowband filters with the wide upper stopband.

2. DUAL-MODE RESONATOR

The suspended stripline resonator is arranged on a dielectric substrate suspended inside a metal case (Fig. 1) [10]. It has four strip conductors. The longest conductor with open-circuited ends is placed on the upper side of the substrate. It is folded in the form of a hairpin. There are spacings between its edges and metal sidewalls. All other conductors are placed on the lower side of the substrate. Two of them are disposed opposite the open ends of the upper conductor. One of their ends is closed to the sidewall of the metal case. The third lower conductor is disposed opposite the middle of the upper conductor. It makes this resonator different from all known resonators. One of its ends is closed to the opposite sidewall. The second resonant frequency can be lowered considerably compared with the first resonant frequency because the middle lower conductor has capacitive coupling with the upper conductor in its voltage antinode segment. That is a precondition for functioning of a dual-mode filter.

The resonant properties of the resonator near two first resonances can be studied approximately with the equivalent circuit shown in Fig. 2. This circuit has two oscillation modes: even mode and odd mode. Their frequencies are defined by

$$\omega_e = \sqrt{\frac{2C + C_m}{(L + L_m)C\,C_m}}, \qquad \omega_o = \frac{1}{\sqrt{(L - L_m)C}}. \tag{1}$$

Here the oscillation mode having the currents in the inductors of the

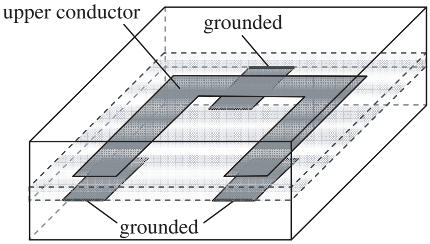

Figure 1. A novel dual-mode suspended stripline resonator.

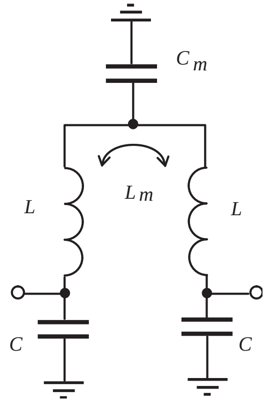

Figure 2. A simplified equivalent circuit for the dual-mode resonator.

same direction we call an even mode. Its frequency ω_e goes up to infinity when the capacitance C_m approaches to zero. Therefore, ω_o is the first resonant frequency and ω_e is the second one if C_m is not too large.

When C_m grows, the frequency ω_o remains constant and the frequency ω_e decreases. According to (1) the frequency ω_e meets ω_o when

$$C_m = (L/L_m - 1)C \tag{2}$$

and then continues to decrease being the first resonant frequency.

The resonant frequencies of coupled oscillations are related with the coupling coefficient at the resonant frequency by the formula [11]

$$k = \left(\omega_o^2 - \omega_e^2\right) / \left(\omega_o^2 + \omega_e^2\right). \tag{3}$$

Formulas (1) and (3) give

$$k = \left(\frac{L_m}{L} - \frac{C}{C + C_m}\right) / \left(1 - \frac{L_m}{L}\frac{C}{C + C_m}\right). \tag{4}$$

The total coupling coefficient k is the "sum" of the inductive coupling coefficient k_L and the capacitive coupling coefficient k_C that is defined by the formula [11]

$$k = (k_L + k_C)\,(1 + k_L k_C). \tag{5}$$

Comparison of (4) with (5) gives formulas for inductive and capacitive coupling coefficients

$$k_L = \frac{L_m}{L}, \quad k_C = \frac{-C}{C + C_m}. \tag{6}$$

Thus, equality (2) means that $k_L + k_C = 0$, i.e., two first resonant frequencies coincide when the inductive and capacitive couplings compensate each other.

Besides the two coupled oscillation frequencies ω_e and ω_o, the equivalent circuit has a transmission zero frequency

$$\omega_z = 1\Big/\sqrt{L_m C_m}. \tag{7}$$

The transmission zero arises here because of mutual compensation of the frequency dependent inductive and capacitive couplings at the frequency of the transmission zero, i.e., $[k_L(\omega) + k_C(\omega)]_{\omega=\omega_z} = 0$ [11].

From formulas (1) and (7) it follows that three frequencies ω_e, ω_o, and ω_z coincide simultaneously when equality (2) takes place. Furthermore if $C_m < (L/L_m - 1)C$ then $\omega_o < \omega_e < \omega_z$, and in the opposite case $\omega_z < \omega_e < \omega_o$.

A frequency response of the dual-mode resonator with weak input and output capacitive couplings of the upper conductor is depicted in Fig. 3. It was obtained by the full wave electromagnetic simulation for the resonator whose scaled dimensions are seen in Fig. 4. This layout corresponds to the case $C_m > (L/L_m - 1)\, C$.

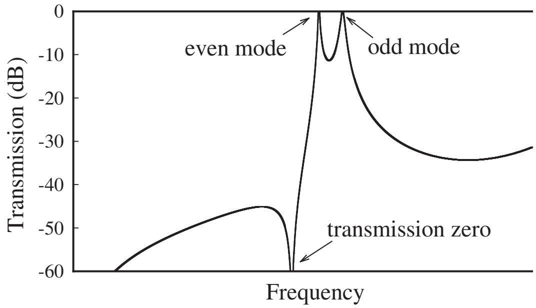

Figure 3. A simulated frequency response for the dual-mode resonator.

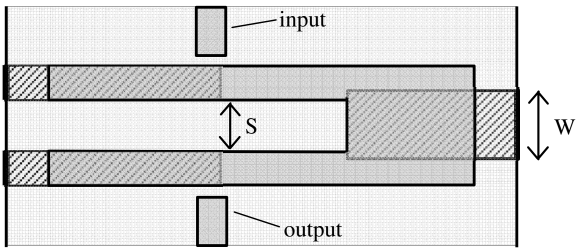

Figure 4. Layout of the dual-mode resonator with capacitive external coupling.

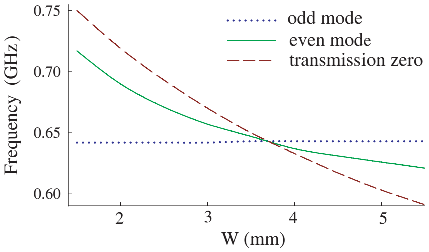

Figure 5. Frequencies as functions of the mutual capacitance width for the resonator with capacitive external coupling ($S = 2.50\,\text{mm}$).

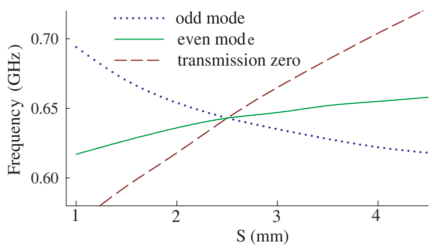

Figure 6. Frequencies as functions of the mutual inductance spacing for the resonator with capacitive external coupling ($W = 3.69\,\text{mm}$).

Dependences of the frequencies ω_e, ω_o, and ω_z on the structure parameters W and S (Fig. 4) are plotted in Fig. 5 and Fig. 6. They are in a qualitative agreement with formulas (1) and (7) since C_m is an increasing function of W and L_m is a decreasing function of S.

Graphs in Fig. 5 and Fig. 6 show that either of the parameters W and S may be used for adjusting the difference between two resonant frequencies. The absolute value of the difference may be arbitrarily small. That means the proposed resonator is good for design of dual-mode narrow-band filters.

Note the equivalent circuit in Fig. 2 and formulas (1), (6) give true general qualitative relations between resonant frequencies and structure parameters of the resonator. The quantitative relations for a particular case may be obtained only with a full wave electromagnetic analysis.

Another way for organizing the external couplings of the resonator is the way where the input and output ports are taps on two grounded conductors under the ends of the upper conductor. This type of external coupling is good for the narrow bandpass filters. It is obvious that as the port is moved closer to the grounded end, the coupling is weaker.

Dependences of the frequencies ω_e, ω_o, and ω_z on the parameters W and S for the tap way of external coupling are plotted in Fig. 7 and Fig. 8. They show that behavior of ω_e and ω_o remain the same as in Fig. 5 and Fig. 6, but ω_z has modified considerably. There are two ranges of parameters. We can see two transmission zeros in the first range and no zero in the second range. That is accounted for the port position affects the voltage and current distributions along the conductors and therefore affects the frequency dependence of the

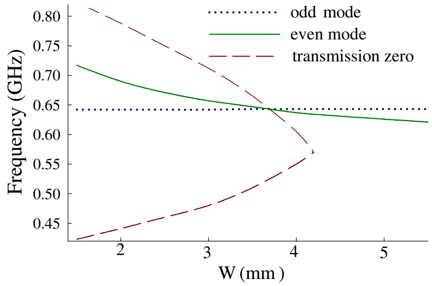

Figure 7. Frequencies as functions of the mutual capacitance width for the resonator with tap external coupling.

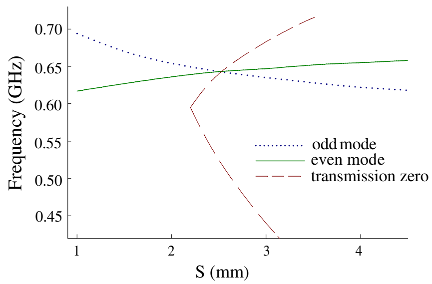

Figure 8. Frequencies as functions of the mutual inductance spacing for the resonator with tap external coupling.

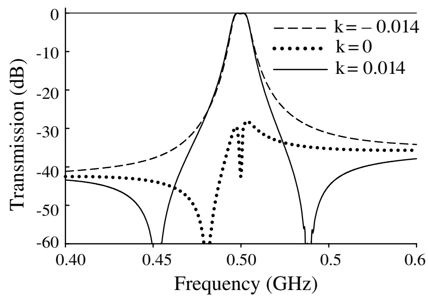

Figure 9. Simulated frequency responses of the resonator with taps on grounded conductors for three coupling coefficients.

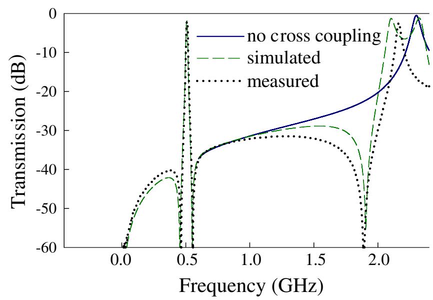

Figure 10. Frequency response of the one-resonator dual-mode filter with tap external coupling.

coupling coefficient $k(\omega)$ outside the resonant frequency [11]. Similar effects in a suspended stripline and microstrip filters with tap external coupling were described in [8, 12].

Note that the point where two zeros meet and disappear may be either above or below the frequency of the mode crossing. It depends on the air thickness h_a between the dielectric substrate and the metal case. As h_a is thicker, the frequency of meeting is higher.

Graphs in Fig. 9 demonstrate the filter performance capabilities of the resonator structure with tap ports on the lower grounded conductors. The structure has two transmission zeros when W is not too wide and S is not too narrow. In this case, we have $\omega_o > \omega_e$, i.e., $k > 0$.

3. ONE-RESONATOR FILTER

The structure of one-resonator dual-mode filter was simulated with CST Microwave Studio®. Its simulated frequency response in a wide frequency range is plotted with a solid line in Fig. 10. This response has the fractional 3-dB bandwidth of 2% and the upper fractional stopband of about two octaves. However, the transmission in the upper stopband is not low enough.

Cross coupling topologies are widely used to introduce additional transmission zeros for bandpass filter applications. Methods to design cross-coupling filters have been reported in numerous papers [13–15].

In the considered filter construction, we produce an additional transmission zero in the upper stopband with an additional coupling element (short conductor) placed on the upper substrate side opposite to the ends of the long folded conductor. The photograph of the manufactured filter having the additional coupling element is shown in Fig. 11.

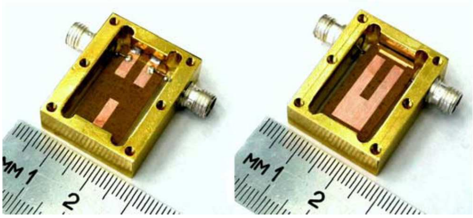

Figure 11. Photographs of the manufactured one-resonator dual-mode filter with tap external coupling (bottom and top views of the resonator without covers).

The substrate of dimensions 0.5 mm × 12 mm × 22 mm was made of microwave ceramics with the dielectric constant $\varepsilon_r = 80$. The air thickness was $h_a = 4\,\text{mm}$.

The measured frequency response of the manufactured filter is plotted in Fig. 10 with a dotted line. The measurement has been carried out with Rohde & Schwarz®Vector Network Analyzer. The simulated response for the same construction is plotted here with a dashed line. It is seen the additional coupling element improves the filter performance in the upper stopband but does not affect the response in the passband. The measured minimum insertion loss in the passband is about 2 dB.

4. TWO-RESONATOR FILTERS

We have considered two constructions of the two-resonator dual-mode filter. In the first construction, two dual-mode resonators having input and output taps are cascaded with a short connective conductor. Any other couplings between the resonators are neglected. Because the taps are situated near the ground and the connective conductor is short, the additional spurious transmission peak is generated far from the passband. The simulated frequency response depicted in Fig. 12 proves that. The filter has the 3-dB fractional bandwidth of 2%.

Thus, the first construction is rather simple for design. Here a passband transmission ripple caused by coupling disproportion is easy eliminated by adjusting internal tap coupling. As for a ripple caused by frequency misbalance it is easy eliminated by putting any asymmetry into the resonator, e.g., widths of left and right parts of the resonator or offset of the middle grounded conductor.

In the second construction, two dual-mode resonators are coupled electromagnetically all over their length. This construction is more difficult in design but more simple in manufacture. Its adjustment is similar to adjustment of the first filter.

The second filter was manufactured on a ceramic substrate that had dimensions $0.5\,\mathrm{mm}\times7\,\mathrm{mm}\times14\,\mathrm{mm}$ and dielectric constant $\varepsilon_r = 80$. The air thickness was $h_a = 2.1\,\mathrm{mm}$.

The frequency response of the filter is plotted in Fig. 13. The inset shows both the transmission and the reflection near the pass band. Four reflection minimums are seen in the inset. Therefore, the two-resonator filter has a performance of a fourth order filter.

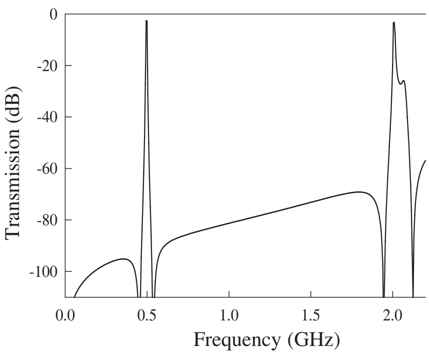

Figure 12. Simulated frequency response of the dual-mode filter with two cascaded tapped resonators.

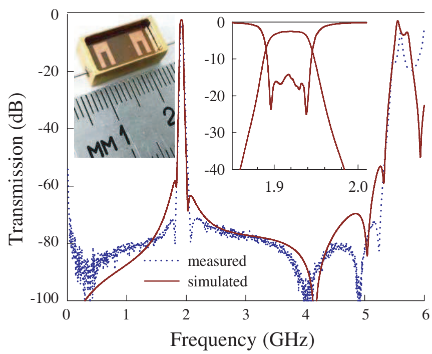

Figure 13. Frequency response of the filter with two electromagnetically coupled dual-mode resonators.

The filter has the center frequency of 1.93 GHz, the fractional 3-dB bandwidth of 2 %, and the measured minimum insertion loss of 2.6 dB. High symmetry and high steepness of the passband skirts is an important advantage of the filter.

5. CONCLUSION

A novel compact dual-mode suspended stripline resonator is proposed. Its two first modes have close resonant frequencies. Their difference can be easy tuned by adjusting structure parameters. The frequency of the third mode is far from two first ones. Therefore, the resonator is good for narrowband bandpass filters with the wide upper stopband.

Examples of the narrowband bandpass filters having one and two resonators are considered. Simulated and measured frequency responses of the filters are presented. The filters have low insertion loss in the passband. Transmission zeros in stopbands substantially improve the filter performance.

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