Feeder Realization for Quasi-lumped Multilayer Resonators with Low Q-factor

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Abstract: - A novel feeder realization for a quasi-lumped multilayer resonator with low external *Q*-factor is proposed. The resonator is realized as a double-sided microstrip resonator with two quasi-lumped elements: a square spiral inductor and a microstrip patch capacitor. Each quasi-lumped element is printed on separate layer (the upper and the lower dielectric layers are separated by a common ground plane). In this paper, we propose two types of the input/output coupling structure. The resonator inductor is coupled by (1) coupled-lines or (2) saw-toothed structure. The saw-toothed coupling structure is used to increase coupling at the feed port, i.e. realize a lower external quality factor. The design methodology is exemplified by a second-order multilayer bandpass filter that is based on the proposed feeder realization.

Key-Words: - External Q-factor, multilayer resonator, double-sided microstrip, saw-toothed coupled structures

1 Introduction

Microwave bandpass filters are indispensable components in RF front-ends of modern wireless communication systems. Since most mobile devices leave limited space for the placement of filters, it is of importance to miniaturize the required filter size. In the dual-plane approach, the arrangement of components is not longer limited on the single plane and, thus, the design becomes flexible. The fabricated components end up with the three-dimensional structure that reduces the occupied planar size [1]-[2].
In this paper, we investigate a novel feeder realization for a quasi-lumped multilayer resonator with the goal to minimize the external *Q*-factor. The input/output coupling structure of the filter is designed with care to provide an adequate amount of coupling. The coupling is realized interdigitally with saw-toothed coupled structures [3].

The proposed coupling structure is exemplified by a second-order bandpass filter designed for the center frequency of 1.6 GHz on an RT/duroid 5880 substrate with the permittivity of $\varepsilon_r = 2.2$, thickness of $h = 1.575\,\text{mm}$, dissipation factor of $\tan\delta = 0.001$, and metallization thickness of $t = 18\,\mu\text{m}$.

2 Realization of Multilayer Resonator and Feeder

The analyzed resonator is composed of three elements, i.e., the square spiral inductor in the top plane, the connecting via through the substrate, and the microstrip patch in the bottom plane. Fig. 1 shows a three-dimensional electromagnetic (3D EM) model of the proposed multilayer resonator (spiral-via-patch resonator) [4].

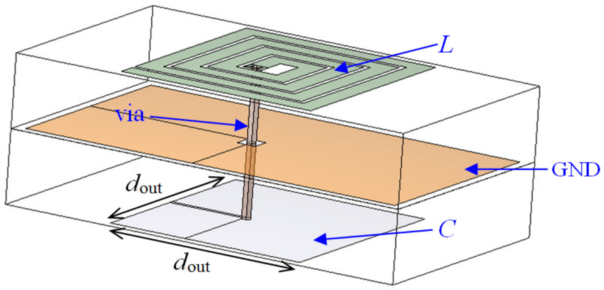

Fig. 1. 3D EM model of the multilayer resonator.

First, we analyze the case when the resonator inductor is coupled by coupled-lines (Fig. 2).

The feed line has a shape as "L" and it is coupled along the central and the sidelong part with two sides of the resonator inductor. For the resonant frequency of 1.6 GHz, the resonator has a size of only $4.6\,\text{mm} \times 4.6\,\text{mm}$ $(0.036\lambda_g \times 0.036\lambda_g)$ [4]. The parameters of the square spiral inductor are N (number of turns), w (spiral line width), s (turn spacing), and d_{out} (effective outer dimension), Fig 1. Dimensions are given in Table 1. The capacitor patch has a square shape with the area of $d_{out} \times d_{out}$.

Table 1. Dimensions of the square spiral inductor.

N	w [mm]	s [mm]	d_{out} [mm]
4	0.4	0.1	4.6

There are eight configurations to achieve the desired coupling between the resonator and the feed lines. Each configuration is designated by two numbers: the first number refers to coupling between the central part of the feed line and a segment of the resonator inductor. Enumeration of inductors segments is shown in Fig. 3.

Another way of fine-tuning Q-factor is changing the length (l) of the sidelong part of the feeder (Fig. 4). Five lengths of the feeder's sidelong part are analyzed: $0\,\text{mm}$, $1.2\,\text{mm}$, $2.4\,\text{mm}$, $3.6\,\text{mm}$, and $4.7\,\text{mm}$.

The external Q-factor is measured versus the width of the gap (d) of the coupled-line structure (Fig. 2). Using the extraction technique provided in [5], the external quality factor associated with the proposed coupling is found between 30 and 100, while the unloaded quality factor is about 145.

Generally, the external quality factor decreases with increasing the length of the sidelong part of the feeder and decreasing the gap between the resonator and the feeder. When the resonator and feeder are coupled with segments 1 and 2, the change of external quality factor versus the gap is slower.

With the proposed feeder realizations, the same values of quality factors can be obtained, but with different distances from the inductor and different sidelong parts of the feeder. However, these different feeder realizations have strong impact on filter characteristics, especially, the filter selectivity. Figures 5-13 show the external quality factor versus the gap (d) for different lengths of the feeder's sidelong part (l). Better insight into the quality factor values is presented in Fig. 13, when the length of the feeder's sidelong part is maximal. Each feeder configuration corresponds to a particular filter realization. For example, when two resonator inductors are mutually coupled with their first segments then the coupling between feeder and resonator is limited to the coupling configurations 32 and 34.

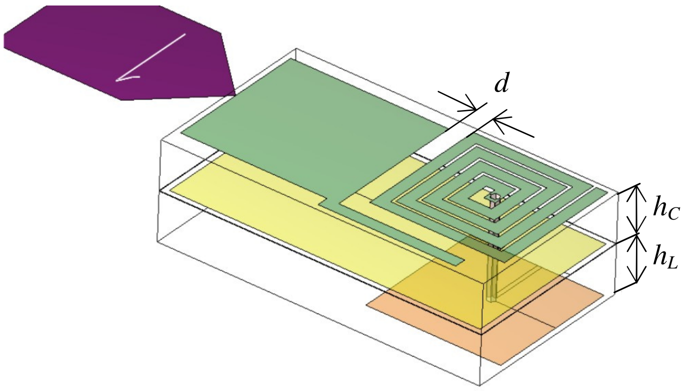

Fig. 2. 3D EM model of the multilayer resonator with the coupled-lines feeder realization.

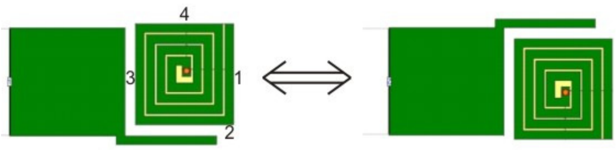

Fig. 3. Enumeration of the inductor segments and the equivalence between inductor coils in clockwise and counterclockwise direction (32) (both structures have same values of the external Q-factor).

This configuration has not provided an adequate amount of coupling, i.e. the desired relatively low value of the external Q-factor required to satisfy the filter specification.

Therefore, an alternative realization of the feeder has been considered. The alternative is based on interdigital coupling, as shown in Fig. 14, and is referred to as the saw-toothed coupling structure [3].

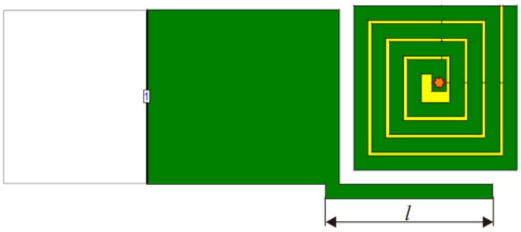

Fig. 4. The first case of coupling between resonator inductance and feeder.

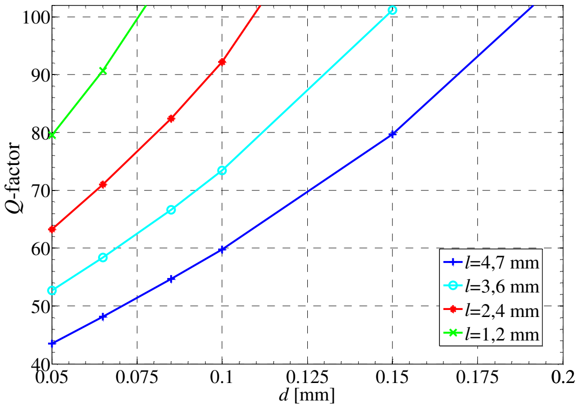

Fig. 5. Q-factor for coupling configuration 14.

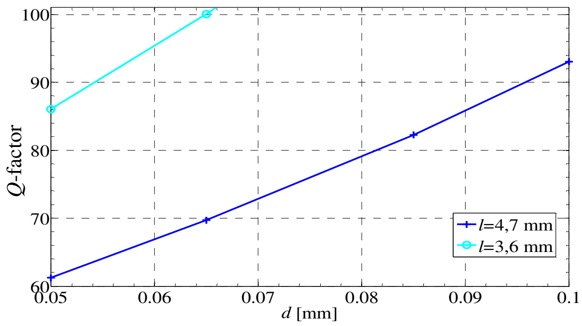

Fig. 6. Q-factor for coupling configuration 43.

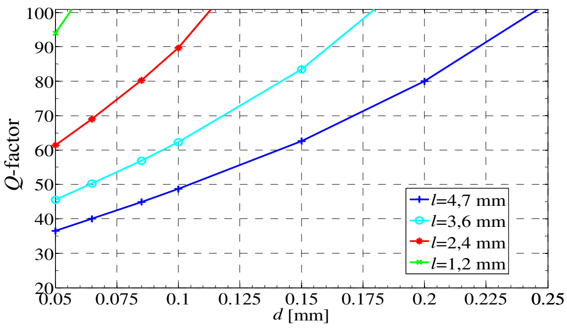

Fig. 7. Q-factor for coupling configuration 21.

The external quality factor for the quasi-lumped multilayer resonator with the saw-toothed coupling structure is shown in Fig. 15.

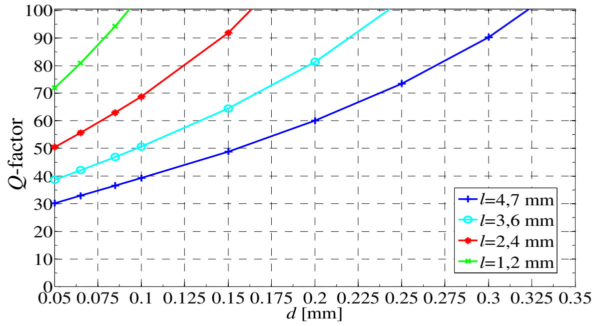

Fig. 8. Q-factor for coupling configuration 12.

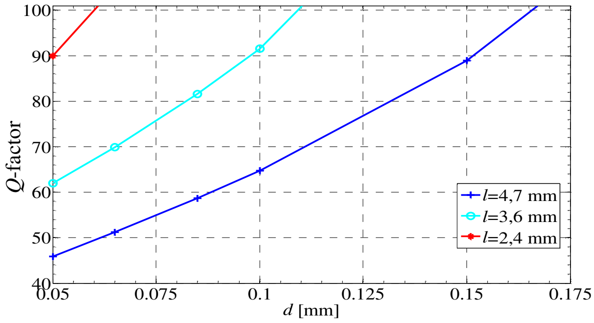

Fig. 9. Q-factor for coupling configuration 32.

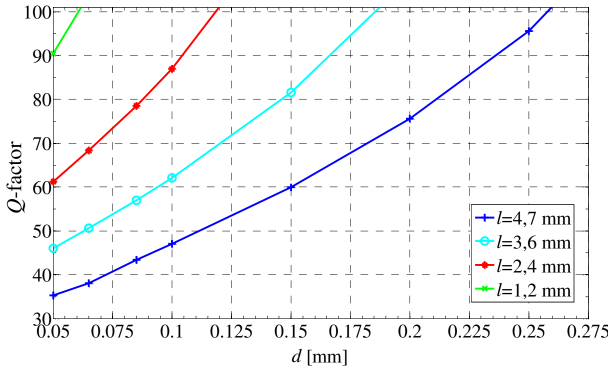

Fig. 10. Q-factor for coupling configuration 23.

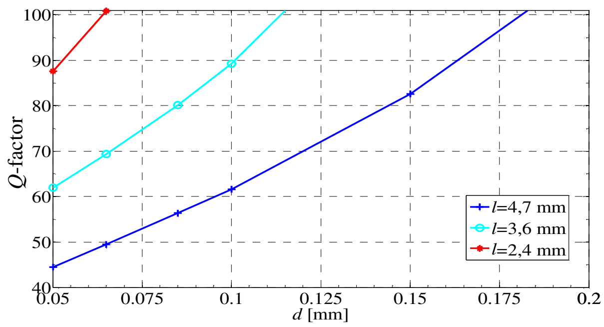

Fig. 11. Q-factor for coupling configuration 34.

The approximate lumped-element equivalent circuit of the proposed resonator is presented in Fig. 16, and the extracted lumped-element values are given in Table 2 [6]. Details of the inductor modelling are shown in Fig 17.

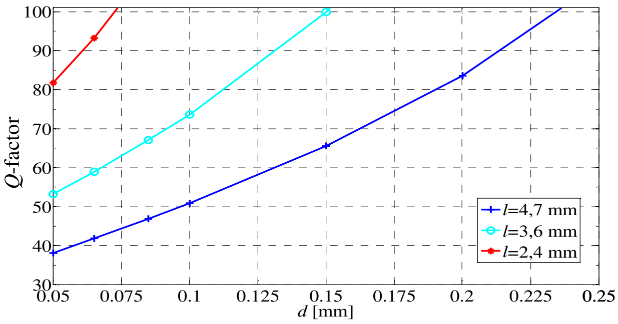

Fig. 12. Q-factor for coupling configuration 41.

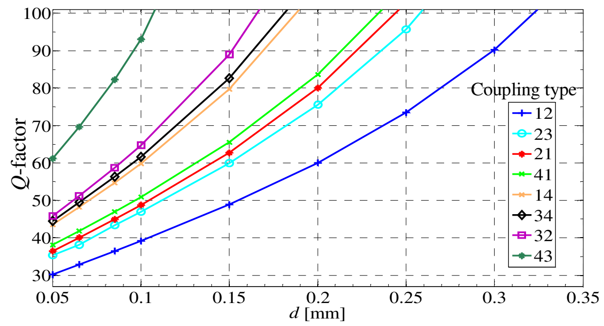

Fig. 13. Q-factor for all the coupling configurations when l=4,7 mm.

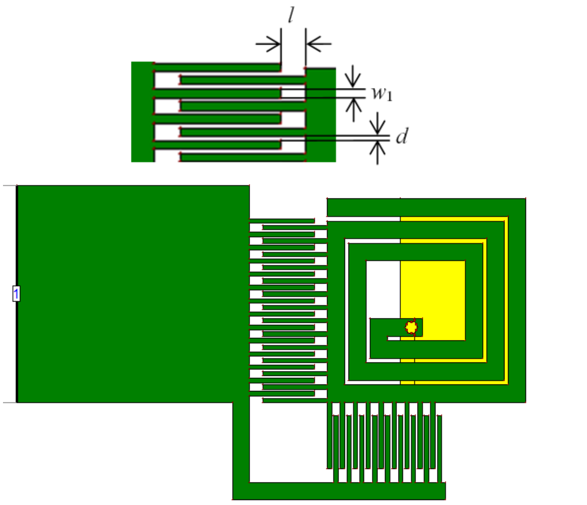

Fig. 14. 3D EM model of the multilayer resonator with the saw-toothed coupling structure.

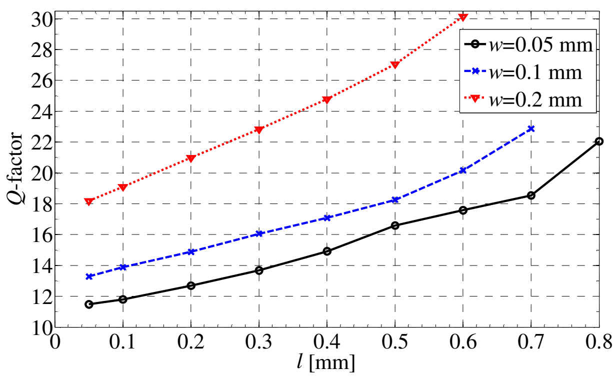

Fig. 15. External quality factor for the quasi-lumped multilayer resonator with the saw-toothed coupling structure ($d = 0.05\,\text{mm}$).

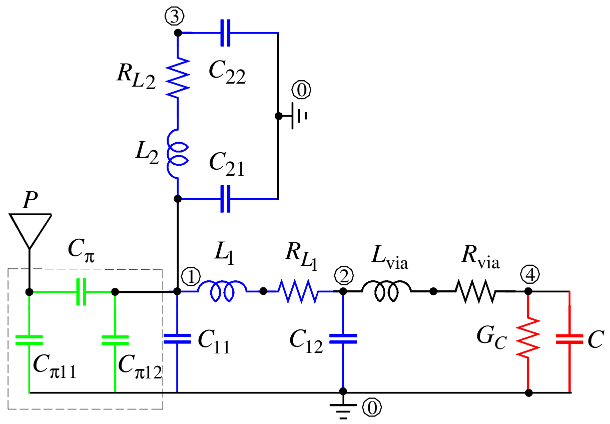

Fig. 16. Circuit model for the resonator shown in Fig. 14.

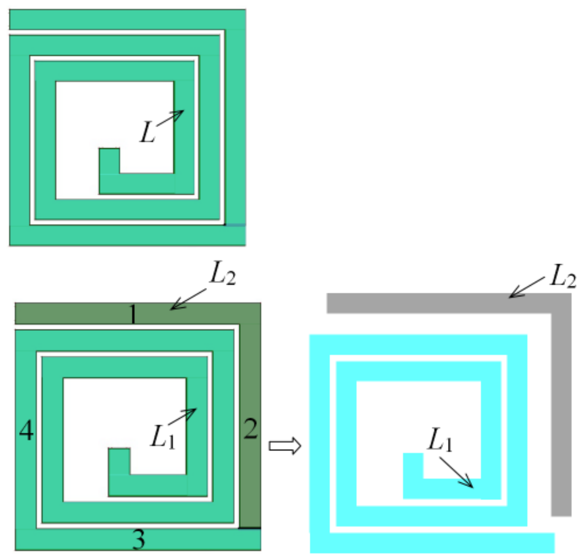

Fig. 17. Modelling of the spiral inductor according to the circuit model in Fig. 16 where $L \approx L_1 + L_2$.

Table 2. Extracted lumped-element values of the resonator shown in Fig. 14.

Loaded Part of **Inductor**		**Capacitor**				**Via**	
L_1 [nH]	R_{L1} [Ω]	C_{11} [pF]	C_{12} [pF]	C [pF]	G_C [μS]	L_{via} [nH]	R_{via} [Ω]
21.85	1.55	0.21	0.25	0.41	5.83	1.7	0.54

Unloaded Part of **Inductor**				**Interdigital Feeder**		
L_2 [nH]	R_{L2} [Ω]	C_{21} [pF]	C_{22} [pF]	C_π [pF]	$C_{\pi 11}$ [pF]	$C_{\pi 12}$ [pF]
6.51	0.29	0.11	0.11	1.06	0.15	0.13

The resonant frequency can be obtained from the expression from the scattering parameter given by:

$$S_{11} = \frac{Y_0 - Y_{\text{in}}}{Y_0 + Y_{\text{in}}} \quad (1)$$

where Y_{in} is

$$Y_{\text{in}} = \cfrac{1}{\cfrac{1}{s\left(C_{11}+C_{21}+C_{\pi 12}\right)+\cfrac{1}{sL_2+R_{L_2}+\cfrac{1}{sC_{22}}}+\cfrac{1}{sL_1+R_{L_1}+\cfrac{1}{sC_{12}+\cfrac{1}{\cfrac{1}{sC+G_C}+sL_{\text{via}}+R_{\text{via}}}}}}+\cfrac{1}{sC_{\pi}}}+sC_{\pi 11}. \quad (2)$$

Figure 18 shows the simulated response of the multilayer resonator: solid curve (LC) is generated from the circuit model of Fig. 16, dashed curve (EM) is generated from the 3D EM model of Fig. 14.

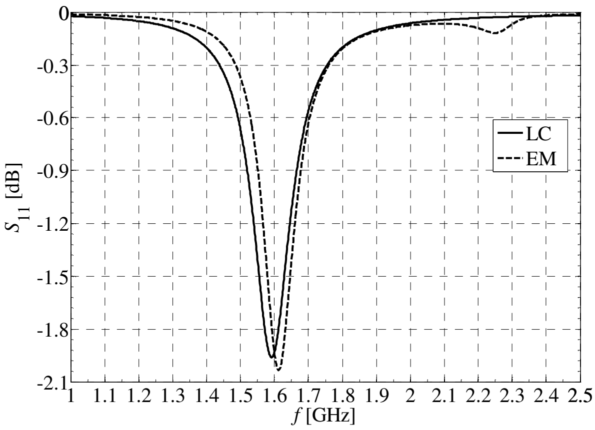

Fig. 18. Simulated frequency response of the resonator.

3 Application Example: Second-order Filter and Simulation Results

To demonstrate the feasibility of realizing a filter with the proposed resonator (shown in Fig. 14), a second-order bandpass filter is designed with the center frequency f_0 of 1.6 GHz and 3dB fractional bandwidth of 10.4% (Fig. 19).

The coupling coefficient between the two resonators is $K_{12} = 0.0935$. The external quality factors associated with the resonators and feeder are $Q_{\text{ei}} = Q_{\text{eo}} = 14.9$ (Fig. 15) and the feeder dimensions are $d = 0.05\,\text{mm}$, $w_1 = 0.05\,\text{mm}$, $l = 0.4\,\text{mm}$ (Fig. 14). To meet the requirements, we have chosen the coupling gap d_{12} of $0.3\,\text{mm}$ (Fig. 20).

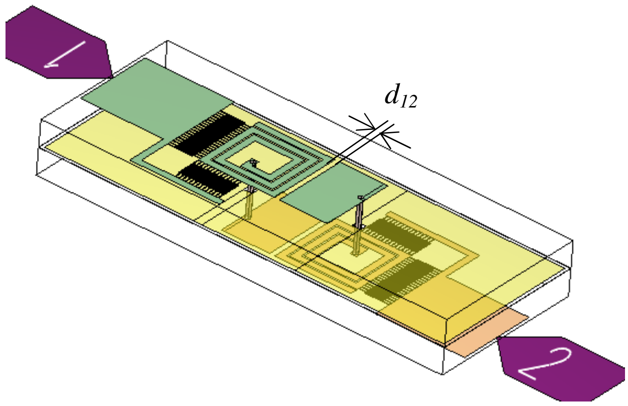

Fig. 19. 3D EM model of the multilayer filter.

The filter ports increase the resonator capacitance and decrease the resonant frequency. Thus we have reduced the length of the spiral inductor for about 1.375 turns and the corrected capacitor dimensions are $2.9\,\text{mm} \times 4.6\,\text{mm}$.

The simulated response of the example filter is shown in Fig. 21. The filter has an insertion loss of 0.92 dB at the central frequency.

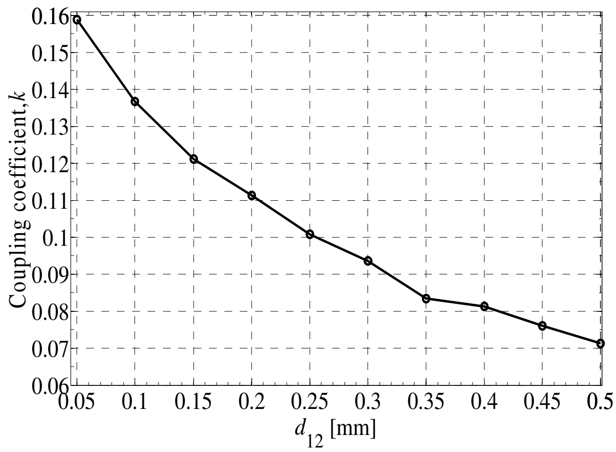

Fig. 20. Coupling coefficient for the quasi-lumped multilayer filter.

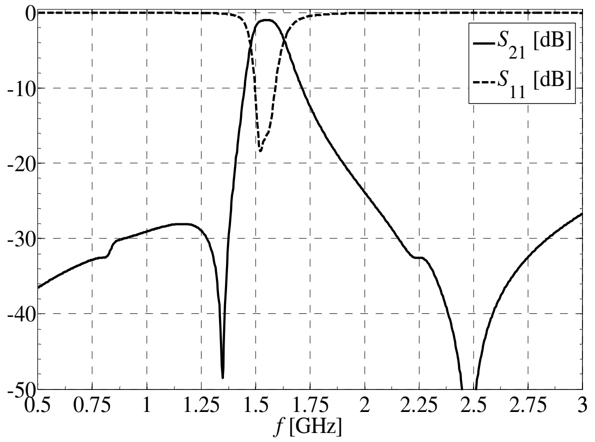

Fig. 21. Simulated *S*-parameters of the multilayer filter.

4 Conclusion

We have studied feeder realization for a low external *Q*-factor for a quasi-lumped multilayer resonator. The multilayer resonator which is implemented on a double-sided microstrip, with two quasi-lumped elements: a square spiral inductor and a patch capacitor. In this paper, the two types of the feeder-resonator coupling structure are proposed: coupled-lines and saw-toothed coupling. To achieve a lower external quality factor, coupling at the feed port is realized by the saw-toothed structure.

Design and realization of a feeder for quasi-lumped multilayer resonators with low Q-factor have been presented. Design has been validated by EM simulations of the second-order multilayer bandpass filter based on the proposed feeder.

Acknowledgments

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