A Frequency-Variant Coupling Structure for Inline Rectangular Waveguide Filters

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***Abstract*— This paper introduces a new resonant coupling structure for inline rectangular waveguide filters. The proposed structure consists of a rectangular cavity placed on top of the main waveguide, and it exploits the TE_{102} mode for creating a frequency-variant coupling capable of producing one transmission zero (TZ). An equivalent circuit characterized by the frequency of the TZ and the slope parameter X_{eq} of the proposed stopband was used in order to realize a filter straightforwardly. Since no internal elements produce any discontinuities, very high values of the X_{eq} are achievable, which allows for placing the TZ closer to the passband while still proving high Q-factors. The design of a 4-pole with a TZ in the upper stopband is illustrated, and the filter was fabricated and measured for validation purposes.**

***Keywords*— Bandpass filter, frequency-variant coupling (FVC), transmission zero (TZ), rectangular waveguide filter.**

I. Introduction

Frequency-variant couplings (FVCs) are alternative solutions for filters to implement transmission zeros (TZs) in an already congested spectrum, which nowadays requires even more selective filters. Some standard solutions, however, are often unsuitable for the intended applications since the overall size can be a constraint (due, for instance, to the multiple paths needed for cross-coupling) or even when more complex structures, which can make it more difficult to determine precisely the position of the TZ. Instead, FVCs offer a different choice for simple topologies with the possibility of having full control of the TZ. Additionally, the implementation of TZs is not introduced by the main cavities, which facilitates the design process, making it less cumbersome. Under this context, some solutions involve using a special discontinuity inserted inside the filter. TZs are introduced when such discontinuities, in addition to realize the coupling between the adjacent cavities, also behave as resonant structures. Various discontinuities with these properties have been proposed for waveguide filters [1]–[3], and combline [4]. The most popular is the partial-height post [1], whose main benefit is undoubtedly its compactness since all the elements are included inside the waveguide. On the other hand, there is a noticeable drawback, represented by the most significant realizable value of the slope parameter, which is relatively tiny, limiting, as a result, the position of the TZs. Indeed, the closer the TZ is to the passband, the larger the required slope parameters.

In other words, the discontinuity in the middle of the propagation path considerably limits the ability to place the TZ very close to the passband. One solution involving elements inside the waveguide was proposed in [5], with a small post close to the cavity wall. This solution can provide very high values of the slope parameter. However, the structure is extremely sensitive to small changes, and manufacturing becomes quite challenging. Additionally, close TZs will suffer from higher losses. A solution that overcomes the problem of placing the TZ very close to the passband while providing a high Q-factor is using external elements that also work as resonating structures. This can help to boost the Q-factor generated by the resonance more than the one provided by the partial-height posts. The fundamental idea is to use singlets as a way to introduce TZs. A more current solution, presented in [6], uses an oversized rectangular cavity that operates with the higher order mode TE_{301}. Such a structure also considers the TE_{10} mode, which propagates through the filter bypassing energy and creates a virtual path between source and load, resulting in source-to-load coupling.

In this paper, an alternative solution is proposed. In this case, the FVC element consists of a cavity placed above the filter (along the E-plane) and connected to the filter through an iris. This can be a good alternative to the one presented in [6] when you have to save space in the lateral part (along

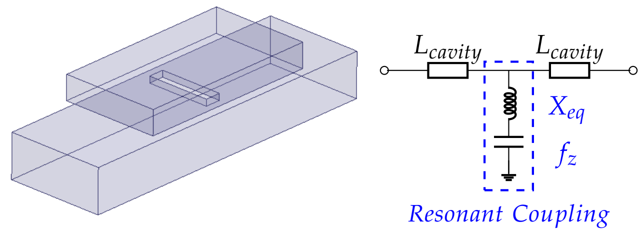

Fig. 1. Resonant coupling structure and its equivalent circuit.

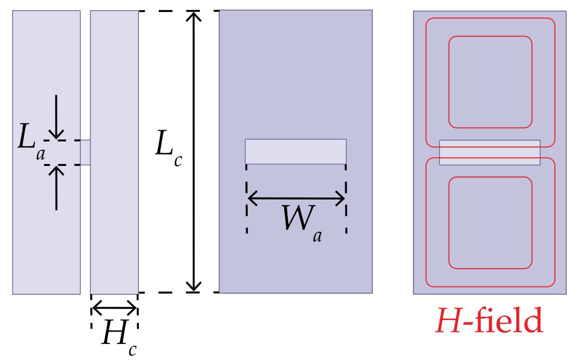

Fig. 2. Parameters and fields of the resonant coupling structure.

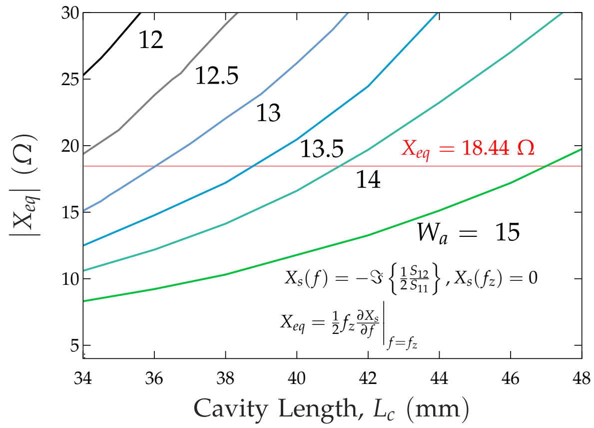

Fig. 3. Representation of the X_{eq} versus the cavity length for different aperture widths of the iris (W_a). Height = 5.7 mm, length of the iris = 3.5 mm, iris thickness = 1.5 mm.

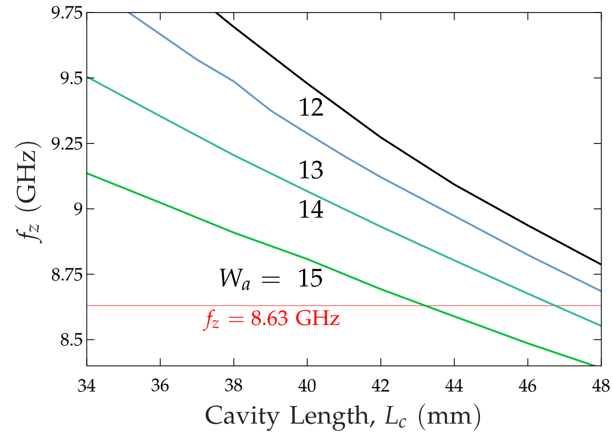

Fig. 4. Representation of the f_z versus the cavity length for different aperture widths of the iris (W_a). Height = 5.7 mm, length of the iris = 3.5 mm, iris thickness = 1.5 mm.

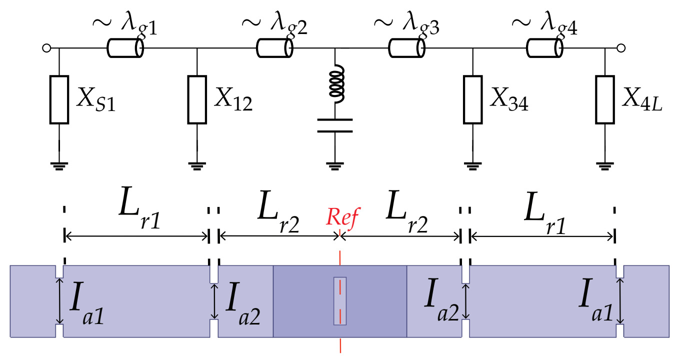

Fig. 5. Equivalent circuit of the 4-pole filter and view of the aimed filter.

the *H*-plane) of the filter.

The structure offers the following advantages concerning previous FVC filters:

- Very high X_{eq} values and several degrees of freedom for accurate control of the X_{eq} and f_z, thus a precise TZ position.
- It can be used in inline waveguide filters without increasing its size laterally.
- It allows high *Q*-factors if needed by considering the parameters that define the resonant coupling structure (e.g., height).
- It can be implemented without an extensive optimization process in a very straightforward approach.

A very high X_{eq} value is needed in the following cases: when the transmission zero is very close to the filter band, when the filter is narrowband, and when higher order modes in cavity filters are exploited. The use of higher order modes can be exploited when low losses are needed. For that reason, the manufactured filter presented in this paper exploits the resonant modes TE_{102}. In this case, the needed X_{eq} value cannot be reached by the classical FVC. Furthermore, considering that the *Q*-factor of the FVC also affects the filter losses, the TE_{102} has been considered even for the FVC. However, it may also work with his fundamental resonance.

II. Stopband Singlet

The proposed stopband singlet is shown in Fig. I. It consists of a rectangular waveguide with a single aperture placed orthogonally to the direction of propagation. Furthermore, even though there are other configurations concerning the position of the apertures, in this work, special attention was paid to this particular one for designing filters.

The proposed structure can be described by the equivalent circuit of Fig. I, and as can be seen, it represents two connected transmission lines that describe the input-output reference of the middle frequency-dependent impedance, which is characterized by the parameters X_{eq} and f_z: X_{eq} represents the slope parameter of the impedance, which changes with respect the frequency, and f_z is the frequency, in which the stopband resonates. Overall, the FVC is designed to obtain the proper value of the inverter and resonate at the frequency where the TZ is desired to be placed.

The physical parameters that defined the structure are depicted in Fig. 2 and the set of equations represented in the inset of Fig. 3 were used for computing the resulting X_{eq} of the structure, and create a series of graphs that link both X_{eq} and f_z to the parameters of the stopband singlet shown in Fig. 2. The values were selected to obtain an inverter operating around 8-10 GHz. In this particular case, it was illustrated X_{eq} and f_z versus the variations of the cavity length (L_c) for various aperture widths (W_a). These two parameters W_a and L_c were mainly considered for the design of a bandpass filter. Nonetheless, the other parameters can be used for adjusting the X_{eq} without affecting considerably the frequency, and it can also be used initially depending on the desired *Q*-factor, for instance, changing the cavity height (H_c).

From Figs. 3 and 4, it can be observed that increasing the aperture width (W_a), lowers X_{eq} and f_z. On the other hand, as expected, when the cavity length increases, the f_z goes to smaller frequencies, and the X_{eq} increases. Thus, by narrowing the iris, for instance, very high values can be obtained, and the frequencies in that case, can be adjusted by

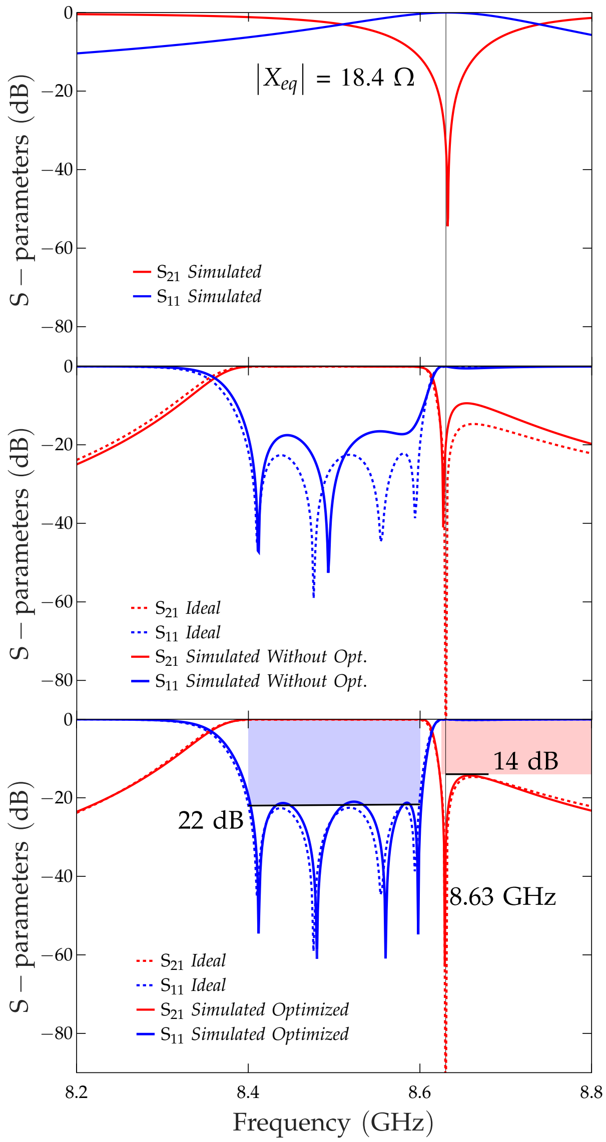

Fig. 6. S-parameters: (above) the stopband singlet; (middle) the 4-pole filter without optimization; (below) after optimization.

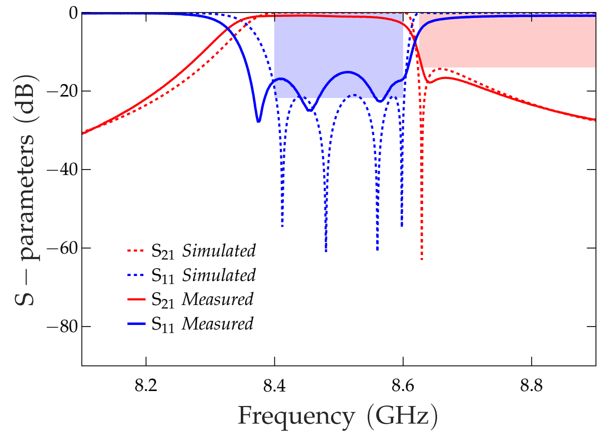

Fig. 7. Measured results of the 4-pole filter.

increasing the cavity length.

III. Filter Implementation

For designing a filter, a 4-poler filter was selected, and the following specifications were considered:

1) Central frequency: 8.4994 GHz; Band: 8.4 - 8.6 GHz.
2) Return loss: 22 dB.
3) Frequency TZ: 8.63 GHz.
4) Input-output waveguide: WR90. Irises with thicknesses of 2.5 mm.

The filter was designed with the procedure introduced in [7] with the mode TE_{102} in order to increase the overall Q-factor of the filter, as indicated previously. The resonant coupling also operates with the TE_{102} mode to similarly increase the Q-factor of the resonance that generates the TZ. In addition to this, the use of the TE_{102} mode also allows a lower sensitivity to manufacturing tolerances. Fig. 5 represents the equivalent circuit as well as the physical representation of the final 4-pole filter.

By considering these specifications, the following lengths and irises were determined: L_{r1} = 47.91 mm, L_{r2} = 53.19 mm, I_{a1} = 14.76 mm, and I_{a2} = 11.89 mm. The obtained slope parameter was X_{eq} = 18.44 Ω.

The dimensioning of the resonant coupling with the structure in Fig. I and the required value of X_{eq} has been carried out with the help of the previous diagrams (Figs. 3 and 4). In fact, several limits can be defined to extrapolate the value of L_c and W_a. By determining the margin of W_a between 14 and 16 mm, the parameters were calculated for L_c between 41.7 and 48 mm, giving the following values: L_c = 44.73 mm and W_a = 14.62 mm.

Fig. 6 shows the scattering parameters of the stopband singlet designed for an X_{eq} of 18.4 Ω at 8.63 GHz. It must be pointed out that the waveguide length connected to the resonant coupling must be adjusted. In this case, the reference misplacement (considering the middle apertures as a reference distance) was obtained by adjusting the right length and ensuring it behaves as an impedance inverter. In this case, providing a 12.6 mm difference should be extracted to L_{r2}. Such a difference allows for a considerable size reduction. Additionally, a small adjustment was applied to the aperture I_{a2} due to the phase correction applied to the length L_{r2}. For other configurations of the FVC, the differences can be very negligible in comparison.

Fig. 6 (middle) shows the simulated results before the optimization. A good agreement between the ideal and the simulated results can be observed, with the TZ fairly close to f_z. The graph below shows the response obtained after the numerical optimization. During the optimization, mainly two parameters have been slightly adjusted: I_{a2} and L_{r2}.

IV. Experimental Results

In order to validate the proposed FVC structure, the 4-pole of the previous section was manufactured. An SLA 3-D printer carried out the fabrication with a resolution of

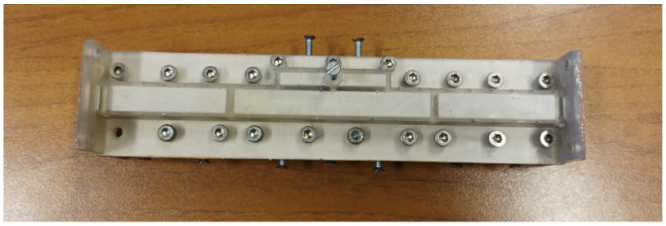

Fig. 8. Photo of the prototype.

0.05 mm through the vertical axis. A cut in the *E*-plane was realized, with tuning screws inserted with an offset of 5 mm to one size. Two tuning screws were inserted in the resonant coupling structure for controlling X_{eq} and f_z.

Measured results are provided in Fig. 7. An average insertion loss value of 0.85 dB was obtained, mainly due to the metalization of the plastic material (Fig. 8). The lower part is shifted by about 47 MHz.

V. Conclusions

A new FVC structure has been introduced in this paper. The structure can generate a TZ with many degrees of freedom for obtaining a wide range of values of the slope parameter, allowing for very high values, which helps for placing the TZ very close to the passband. The FVC structure can help to provide a high *Q*-factor even when the TZ is close, more so if considering higher order rectangular modes. Experimental results showed the feasibility of the proposed structure.

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