High Performance Direct Coupled Bandpass Filters on Coplanar Waveguide

Jeremy K. A. Everard, *Member, IEEE,* and Kwok K. M. Cheng, *Member, IEEE*

Abstract—**This paper describes the design and performance of shunt inductively coupled bandpass filters implemented on open coplanar waveguide. This new structure exhibits low radiation loss due to the removal of the capacitively coupled gaps encountered in end or edge coupled filters. Unloaded Qs greater than 540 have been achieved in unshielded single section resonators at 4 GHz on very thin substrates. These high Qs enable the design of filters with low insertion loss and good stopband rejection. Applications include low insertion loss, high Q printed filters where no screening is required, low noise oscillators and superconducting filters.**

I. Introduction

COPLANAR WAVEGUIDE [1] is a guide medium that is sometimes considered as an alternative to microstrip lines in millimeter-wave integrated circuits. Its principal advantage is the location of the signal grounds on the same substrate surface as the signal line. This eliminates the need for via holes and thus simplifies the fabrication process. It also permits easy connection of both series and shunt components. Coplanar waveguide has been shown [3], [6] to exhibit lower conductor loss than microstrip for a wide range of line impedances. A considerable amount of work [2], [4], [5] on the characterization of CPW as well as on directional couplers and filters can be found in the literature. Previously, coplanar end-coupled bandpass filters [5] have been realized by cutting gaps in the inner conductor of the guide, thus creating capacitively coupled resonant sections. However, these gaps cause high radiation loss because the electric fields in the gaps radiate as two simple dipoles, one at each end of the resonant section, in a way similar to a patch antenna. One possible method to circumvent this problem is to employ a direct-coupled filter structure, Fig. 1, as this does not require capacitive gaps as the coupling elements. This type of filter has been produced elsewhere on coaxial and fin lines [7] and helical lines [10], however, a coplanar waveguide version seems not to have been reported. This filter structure retains all of the advantages of CPW including complete planarity as well as low loss. Furthermore, the radiation loss is greatly reduced by eliminating the coupling gaps and hence high Q performance of the filter is retained in a filter without any screening. This is further demonstrated by placing a metal plate $\lambda/4$ above an

Fig. 1. Layout of a shunt inductively coupled bandpass filter.

unshielded single section resonator. The resonant frequency shifted by less than 0.005% which is 20 times less sensitive than a conventional gap-coupled resonator. In this paper, we shall describe the design procedure and measured performance of two 5 section filters based on this structure.

II. Filter Design

The shunt inductivity coupled CPW filter structure proposed here was designed using filter synthesis techniques as described by Matthaei, Young, and Jones [8]. The filter is composed of half-wave transmission lines and immittance inverters (Fig. 2). The immittance inverters are realized by embedding shunt inductors between negative lengths of uniform transmission lines. For easy fabrication, all the half-wave transmission lines are chosen to have identical characteristic impedance Z_T. Furthermore, without loss of generality, a symmetrical filter structure is assumed. Thus, the circuit parameters $X_j(\omega_o L_j)$ and ϕ_j are given by

$$\frac{Z_o}{X_j} = \left(\frac{Z_o}{S}\right)^{1/2} - \left(\frac{S}{Z_o}\right)^{1/2} \qquad j = 1, n+1 \tag{1a}$$

$$\frac{Z_o}{X_j} = \frac{Z_o}{S}\frac{\sqrt{g_{j-1}g_j}}{g_0 g_1} - \frac{S}{Z_o}\frac{g_0 g_1}{\sqrt{g_{j-1}g_j}} \qquad j = 2, 3, \cdots, n \tag{1b}$$

$$S = \frac{\pi Z_T}{2g_0 g_1}\frac{\omega_2 - \omega_1}{\omega_o} \tag{1c}$$

$$\phi_j = -\tan^{-1}\left(\frac{2X_j}{Z_o}\right) \tag{1d}$$

where ω_o, ω_1, and ω_2 are the center, lower cut-off and upper cut-off angular frequencies; n is the number of resonant sections in the bandpass filter; g_i are the element values of the corresponding lowpass equivalent, and Z_0 is the source and load impedance. The first two equations are used for the evaluation of the shunt inductor values, provided that

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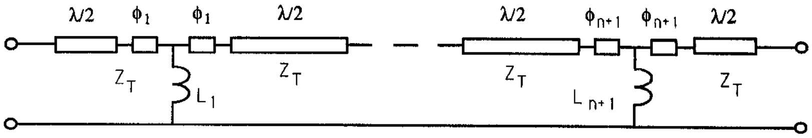

Fig. 2. Schematic diagram of a shunt inductively coupled bandpass filter.

the design parameters (Z_T, bandwidth and ω_o) are known in advance. Note that the negative length of transmission lines of the immittance inverters are simply absorbed in the half-wavelength resonant sections. The shunt inductors are realized by shunt strips with varying width to cover the range of inductance values required.

One method to design the shunt inductors is to use the classical formula for ribbon (straight) inductors,

$$L = 2l\left\{\ln\left(\frac{2\pi l}{w}\right) - 1 + \frac{w}{\pi l}\right\} \qquad nH \tag{2}$$

where w and l, measured in cm, are the width and length of the inductor, respectively. However, the accuracy of this formula is quite poor with errors often greater than 10% for wide lines (small inductance).

An alternative way to obtain the effective inductance of the inductor structure shown in Fig. 3 is to conduct a series of experiments to measure the loaded quality factor (Q_L) and transmission coefficient (S_{21}) of a single section resonator having variable shunt inductance values. These resonators should be made to resonate at roughly the center frequency of the filter. The information thus obtained is then used to determine the value of L from the following relationship

$$Q_L = \frac{\pi}{4} z S_{21}\left\{\left(\frac{Z_o}{2\pi f_r L}\right)^2 + \left(\frac{z-1}{z}\right)^2\right\}$$
$$z = \frac{Z_T}{Z_o}. \tag{3}$$

This equation is valid provided that the quality factor of the inductors is high enough to have insignificant effect on the measurements of Q_L and S_{21}. A plot of measured inductance values versus inductor line width w on 0.062″ RT-5880 substrate is depicted in Fig. 3. The width of the gap l is 1 mm and the ground-to-ground spacing D is 4.5 mm.

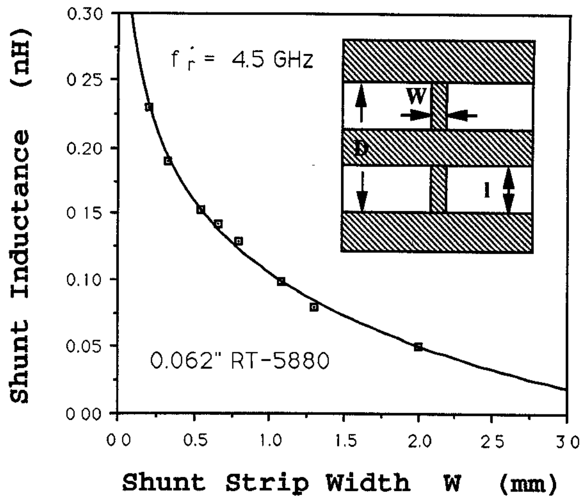

Fig. 3. Plot of effective inductance values versus shunt inductor line width.

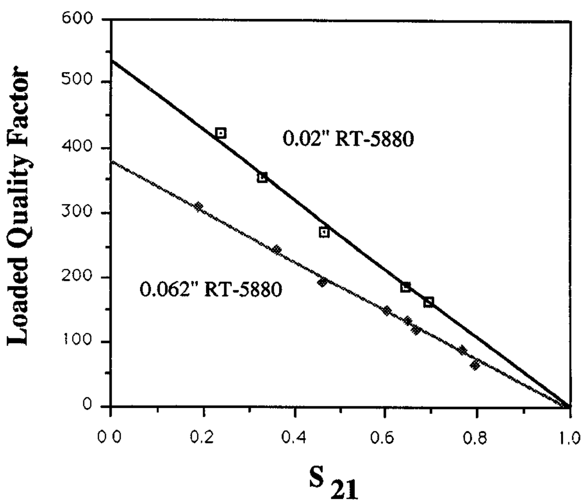

Fig. 4. Plot of loaded quality factor versus S_{21} of single section shunt inductively coupled CPW resonators on two thicknesses of RT-5880 substrate.

III. Determination of Line Loss and Maximum Q_o

For a given substrate material and operating frequency, it is necessary to evaluate the line loss (both conductor and dielectric) of coplanar waveguide to predict the insertion loss of the filter. This data can be extracted from measurements of the loaded quality factor of a number of single-section resonators having a variety of shunt inductors at each end of the transmission line. A plot of the loaded quality factor versus S_{21} of some experimental resonators is shown in Fig. 4. These direct coupled resonators were built on RT-5880 Duroid substrates of two different thickness. The fact that the graphs are almost linear and the intersection at the X-axis is very close to unity indicates that the losses in the shunt inductors are negligible at these measurements points. This observation is best illustrated in Fig. 5 which shows the calculated effects of finite Q factor of the shunt inductors on Q_L of the resonator. In these calculations, the value of Q_o is assumed to be 350 and the value of the inductor Q is assumed to be constant. In practice, the Q factor of the shunt inductors deteriorates as S_{21} approaches unity because of the diminishing inductor width required. Fortunately, the value of Q_o can be determined directly from those measurement points that employ only wide inductors as the shunt elements (low S_{21}). A simple model which only takes into account the line loss of the resonant section can therefore be used to derive the value of Q_o.

If the losses in the shunt inductors are excluded, then

$$Q_o = \frac{Q_L}{1 - S_{21}} \tag{4a}$$

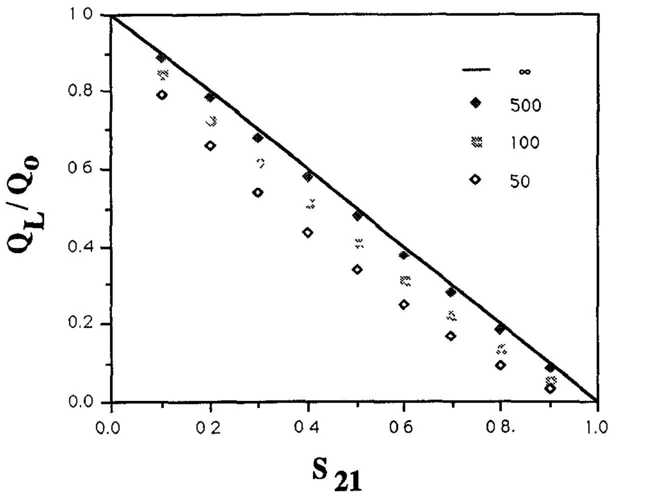

Fig. 5. Simulated degradation of Q_L/Q_0 caused by the finite Q values of the shunt inductors.

$$S_{11} = \frac{Q_L}{Q_o} \tag{4b}$$

where $Q_o = \pi/2\alpha L_r, Q_L$ is the loaded quality factor, S_{21} is the transmission coefficient of the resonator, α and L_r are the attenuation coefficient and length of the resonant sections. Note that Q_o can also be found from the intersection between the extrapolated line and the Y-axis. Two sets of resonators have been tested on different thicknesses of substrates (0.02″ and 0.062″ RT-5880 Duroid). The measured unloaded Q factors are approximately 540 and 380, respectively. A similar resonator on 0.02″ RT-5880 substrate, which is capacitively-coupled has also been measured. The unloaded quality factor thus obtained is only 85 which is caused by high radiation from the gaps. In these measurements, the resonators are unshielded and cross-bonding by means of metallic strips between the two ground planes were not included. In fact, cross-bonding does not appear to alter the direct coupled filter response. Shielding the end-coupled filter does improve the Q factor but both cross bonding and shielding increase the cost and complexity of the filters. An end-coupled resonator on 0.02″ RT-5880 substrate which is shielded shows an unloaded Q factor of about 640.

A parameter to be considered when designing filters is the characteristic impedance of the resonant section. It should be chosen such that the total loss (conductor and dielectric) is at its minimum [6]. This optimum characteristic impedance, of the resonant section, is determined from a series of experiments that measure the unloaded quality factor of resonators of different aspect ratio. The ground-to-ground spacing is kept constant. The optimum point is the impedance value which gives the maximum Q_o.

IV. CPW Filter Experiments

A 5-section filter has been built with a center frequency of 4.6 GHz and a bandwidth of 350 MHz. The filter was designed to have a Chebyshev response with 0.2 dB ripple. The complete filter is fabricated on the thicker substrate (0.062″ RT-5880) to produce a more robust design. The inductance values of L_1 $(L_6), L_2(L_5)$, and $L_3(L_4)$, are calculated to be approximately 0.72, 0.27, and 0.22 nH, respectively. To realize the large inductance value (0.72 nH) required at both ends of the filter, the structure shown in Fig. 6 is adopted in the design. This configuration should be represented by a T circuit rather than a simple inductor, to take into account the phase shift introduced by the series elements. At the time of designing the filter, an accurate model for this structure was not available. Therefore, the design was improved iteratively by adjusting the dimensions of the end inductors until a reasonably flat passband response was obtained.

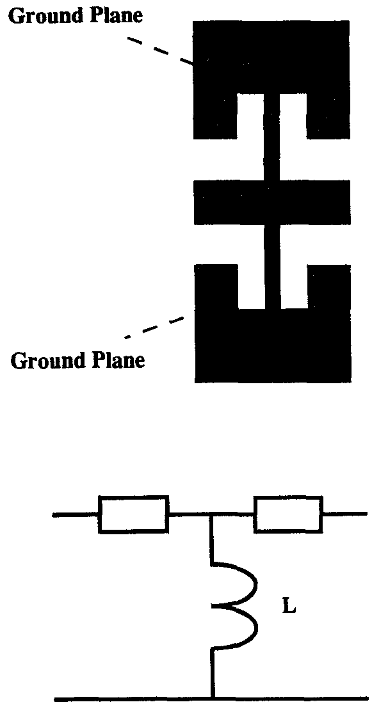

Fig. 6. Structure used for the realization of the large shunt inductors.

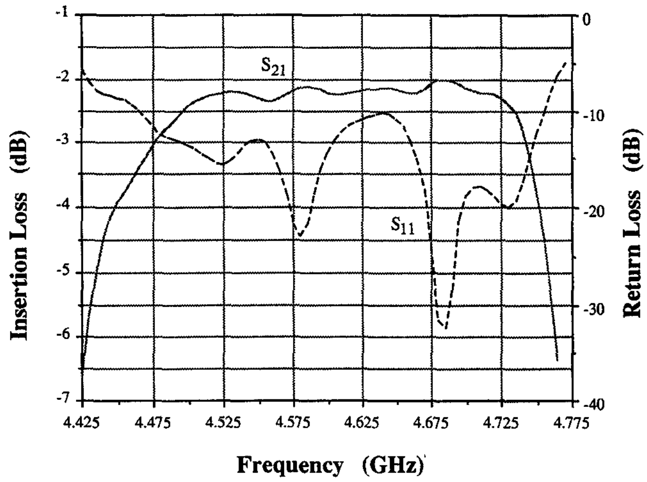

Fig. 7. Filter passband response.

With a ground-to-ground spacing of 4.5 mm, the maximum value of Q_o is found to be 380 where the optimum line impedance of the resonant section is approximately 95 Ω. This optimum value is also found to be in close agreement

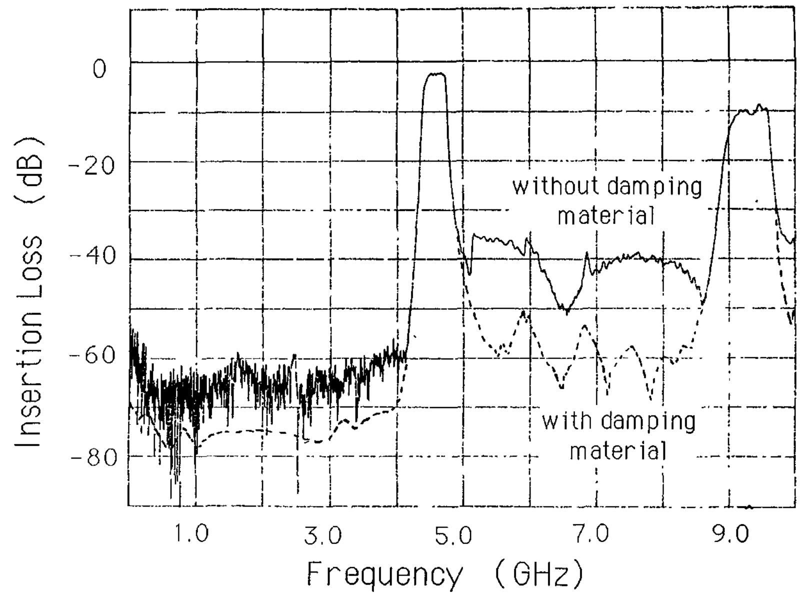

Fig. 8. Measured filter response.

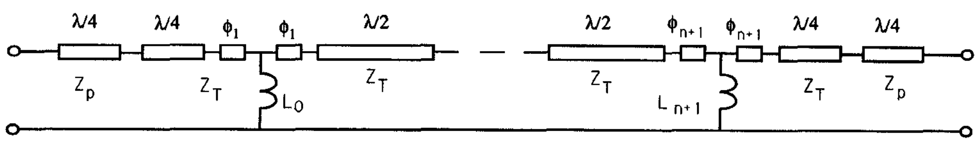

Fig. 9. Modified CPW filter structure with end transformers.

with the theoretical value which are based on the quasi-static assumption [6]. Consequently, the insertion loss of the filter predicted by computer simulation should equal 1.1 dB. The measured responses shown in Figs. 7 and 8 indicate that the filter has a mid-band insertion loss of about 2 dB. The peak to peak ripple within the passband is around 0.4 dB. The discrepancy between the predicted and the measured insertion loss values is believed to be due to the exclusion of the losses in the shunt inductors. By taking into account the significant Q factor degradation in the shunt inductors at the ends of the filter (L_1, L_6), the simulated insertion loss of the filter for inductor Qs of 200, 100, and 50, are approximately 1.3, 1.55, and 1.85 dB, respectively. The Q factor of other shunt inductors (L_2 to L_5) are assumed to be equal to 300. Furthermore, spurious responses are observed above the passband and a possible explanation for this phenomenon is leakage of the signal power into surface waves [9]. Cross-bonding was found to have negligible effect on these spurious responses. The stop-band rejection can be improved by placing absorbing material close to the filter or by shielding.

V. Modified Filter Design with Impedance Transformers

To reduce the insertion loss of the filter, an obvious way is bring the inductance values down to allow wider shunt inductors (higher Q) to be used in the design, in particular the inductance values of the inductors at the ends of the filter. From (1a), it can be shown that there is optimum value of source and load impedance Z_o to minimize $X_j (j = 1, n+1)$

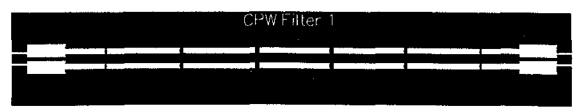

Fig. 10. Layout of the modified CPW filter.

and hence the shunt inductances of the inductors at the ends of the filters. If we differentiate (1a) with respect to Z_o and equate the resulting expression to zero, the optimum value of Z_0 is found to be $3S$ and the corresponding value of X_j is approximately $2.6S$. For shunt inductors $L_j (j = 2, 3, \cdots, n)$, a higher Z_o is preferable for lower inductance values as can be seen from (1b). Since these inductors usually have much lower inductance values than the two inductors at the ends of the filter, it is still worthwhile choosing the optimum Z_o to attain the minimum values for these two shunt inductors. As most microwave subsystems are designed to have a standard characteristic impedance value of 50 Ω, impedance transformers are needed at both ends of the filter. For narrow band designs, a single section quarter-wave transformer is found to be quite adequate. The schematic diagram and physical layout of the modified filter structure are shown in Figs. 9 and 10. The characteristic impedance of the transformer Z_p is simply given by

$$Z_p = Z_T \sqrt{\frac{Z_o'}{3S}} \tag{5}$$

where Z_o' is the external source and load impedance value.

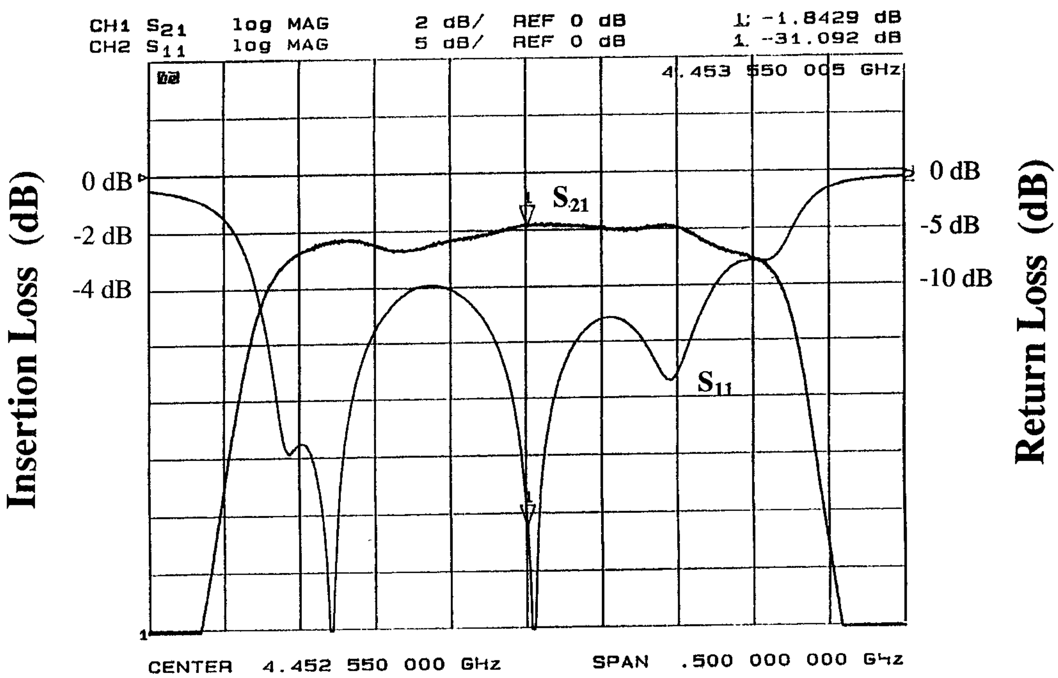

Fig. 11. Bandpass response of the modified CPW filter.

A prototype 5-section CPW filter using modified structure has also been built with a center frequency of 4.45 GHz and 350 MHz bandwidth. The filter is fabricated on 0.025″ Duroid substrate having a relative dielectric constant of 10.2. A high dielectric constant material was used to obtain a more compact design. The optimum line impedance of the resonant section for maximum Q_o is 74 Ω, with a ground-to-ground spacing of 4.5 mm. The unloaded quality factor of a single section resonator is found to be around 320. The optimum value of Z_o is therefore equal to 12 Ω and the minimum value of the two inductors at the ends of the filter is approximately 0.34 nH. Note that this is almost half the value of the inductance required by the previous design. These values can be implemented using a simple structure shown in Fig. 10 which does not require recessed ground planes. The frequency response of the modified CPW filter is shown in Fig. 11. The simulated and measured insertion loss of the filter is approximately 1.4 and 1.9 dB, respectively. The closer agreement between the two values may well indicate that the losses in the two inductors are much reduced compared to the earlier filter design and that the insertion loss of this new filter is limited mainly by the inherent unloaded quality factor of the resonant sections. With lower loss thinner substrates, insertion losses of less than 1 dB ($Q_o > 500$) should be achievable in these unshielded filters.

VI. Conclusions

Experimental results demonstrate that high Q unshielded resonators can be achieved on coplanar waveguide employing shunt inductors as the coupling elements. A 5-section microwave bandpass filter has been implemented based on this structure and the measured performance is shown. The degradation in the filter performance is believed due to the losses in the shunt inductors and further improvements may be obtained by reducing the losses in these elements. A modified filter structure which requires lower inductor values has been demonstrated by adding quarter-wave transformers at both ends of the filter. The filter implementation described here is well-suited to building hybrid, MMIC, and superconducting filters.

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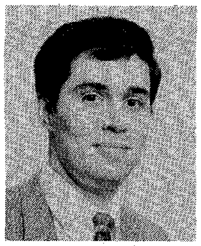

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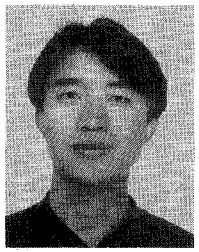

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