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INVESTIGATION OF THE EFFECTS OF FABRICATION TOLERANCES IN MICROWAVE THICK-FILM CIRCUITS

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ABSTRACT

This project dealt with the design and fabrication of bandpass filter centered at 16 GHz using modern thick-film technology. The rapid development of the commercial microwave circuits requires a low cost, cheaper technology to replace the old, more expensive thin-film technology. Therefore, thick-film technology is the best alternative. The effects of fabrication tolerances in the physical dimensions of various parameters were being investigated as well. The analysis of the result can then be applied to determine the trade off between performance and tolerances. It is therefore extremely important to control the variations of parameters in microstrip with fabrication tolerances to achieve the desired performance.

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ACKNOWLEDGEMENTS

A lot of problems have been encountered in the making of this project and I would like to thank few individuals who have made significant contributions for the project to be realized.

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To my friends who contribute directly and indirectly for this project – thanks a lot for your support. You guys are really supportive and I am extremely pleased to have friends like you.

Last but not least, to my beloved parents and siblings back in my home country that pours me with their undivided love and advise. Without you, I may not be here and it is because of you that I am still surviving. Love you so much!

Yours sincerely,

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(SHAHARIL MOHD SHAH)

CHAPTER 1

INTRODUCTION

Thick-film is one of few methods applied to make microwave circuits. It has become a popular method in the low-cost manufacture of hybrid microcircuits at lower-than-microwave frequencies and for densely packaged digital subsystems. Other than that, this method also reduces cost effectively as compared to thin-film technology and monolithic integrated circuit (MIC) technology.

In general, there are two (2) methods normally used to manufacture the thick-film circuits as described below:

1. Thick-film patterns are first printed and fired on to the ceramic substrate. Normally, alumina or an LTCC substrate will be used but occasionally, quarts are more preferred.

2. A printed circuit technique where in this case, etching, will be performed to get the desired pattern in the copper cladding. Plastic and polyolefin substrates can also be used.

These two (2) methods are relatively simpler and less demanding on both equipment and environment than thin-film technology.

CHAPTER 2

LITERATURE REVIEW

Nowadays, the demand for new approaches of circuit technology in microwave circuits and systems is very much needed due to the rapid growth in that area. The increasing applications of microwave circuits in applications such as phased array antennas, satellite communications and car avoidance radar are another stressing factor. Therefore, to fulfil those demands, the search of new circuit technology that offer high performance and yet low in cost is vital. Typical current applications for microwave circuits are as follows [1]:

- Personal telephones
- Wireless local area network
- Satellite telephone systems
- Local distribution microwave systems
- Ground based radar systems
- Intelligent collision avoidance systems for automobiles

Thick-film technology may well answer the above question. It has become well established in the low-cost manufacture of hybrid microcircuits at lower-than-microwave frequencies and for densely packaged digital subsystems [2]. The technology offers low conductor and dielectric losses with good surface finishes and the ability to realise fine conductor geometries. Modern thick-film ink technology have boosted the path into high frequency market areas due to its enhance features as compared to thin-film technology namely photoimageable thick-film techniques. Line resolutions of 12 micron are available together with via dimensions of 50 micron with thick-film technology. In addition, the development of etchable and photoimageable thick-film inks enable conductor tracks to be screen printed and further processed to produce edge definition comparable with traditional etched processes [3]. Good edge definition of film patterns is vital in microwave circuit applications.

Initially, traditional thick-film technology has been developed for microwave integrated circuits (MICs) operating at frequencies up to at least 20 GHz. However, various losses associated with the thick-film conductors combined with tolerancing difficulties tend to restrict production circuits to a maximum frequency of approximately 10 GHz.

Another major drawback of conventional thick-film technology is due to the fact that most dielectric materials generally available are high in dielectric constant (7 or greater) and dielectric loss (10^{-2}).

Conventional thick-film technology has not gain popularity due to various factors. Firstly, thick-film technology is able to resolve microstrip lines very well but it does so with poor edge definition and relatively rough conductor surface. Next, the technology itself is incapable of producing the very fine dimensions required by many essential components in microwave design such as edge-coupled filters, Lange couplers, mixers and circulators. Moreover, it is difficult to realize this structure using thick-film technology since a small coupling gap must be ensured on the outermost resonators. Conventional thick-film technology limits the width of the track and coupling gap to approximately 100 micron but this limitation can be overcome by photoimageable thick-film techniques – an advance thick-film technology.

A more defined way to improve the performance of thick-film technology has developed such technology called KQ which uses advanced thick-film materials in combination with photoprocessing and ceramic substrates to solve many microwave circuit problems. The new technology encompasses of thick-film gold conductors and dielectrics. In this case, novel particle sizing in the gold conductor will allow the printing and firing of a very smooth gold conductor at high density. This in turn will allow the application of a photoresist and the patterning of the conductor by a simple etching process. The dielectric materials use a borosilicate glass based technology which provides low dielectric constant (3.9) and loss (10^{-4}).

There exists another technology namely photoimageable thick-film techniques that can overcome the limitation possessed in conventional thick-film technology. The only difference between both techniques is the fact that the standard thick-film pastes normally used in conventional technology is replaced by a photosensitive material. Photosensitive thick-film pastes originated from the combination of a photosensitive vehicle and metal-glass powders – both of which affect the electrical properties and resolution characteristics.

In addition, this photoimageable thick-film inks will enable the conductor tracks to be screen printed and further processed to produce edge definition comparable with traditional etched processes. In microwave applications, good edge definition of film patterns are of particular important and these new thick-film inks now offer a cheaper alternative to traditional thin-film technology in many such areas.

Therefore, it can be concluded that thick-film technology makes the requirements for the high volume, low cost circuit technologies. However, it must be kept in mind that although cost is the dominant factor, there will be scenarios where the circuit performance is critical. This will result in some low cost technologies that will suffer unacceptable limitations. For instance, in cases of applications which require accurate frequency selection to maximise the use of available frequency spectrum. The same goes in the production of the low loss circuitry that is needed for maximum battery life.

CHAPTER 3
METHODOLOGY AND FACILITIES

3.1 METHODOLOGY

- A circuit simulator will be used to investigate how errors in the geometry of the microwave circuits will affect the performance.

- Fabrication of a typical microstrip component (**i.e.** Band Pass Filter) will be implemented using thick-film technology and comparison will be made between the measured performance and the design performance.

3.2 FACILITIES

- Thick-film fabrication.
- Agilent ADS – a computer aided design (CAD) tool as circuit simulator.

CHAPTER 4
CIRCUIT TYPE

4.1 BANDPASS FILTER

In this project, microstrip lines and components have been chosen since they offer a high performance, compact and low cost microwave circuits. Indeed, there were many circuits, which could have been chosen, but taking into account the design time, fabrication time and test time, a microwave bandpass filter have be considered to be the best option. In order to achieve accuracy in impedance control and good definition of coupler and filter performance, precise geometries must be ensured in the microstrip lines. On the other hand, to obtain low loss in a microstrip-based circuit, the transmission lines must have smooth surfaces, straight edges and high conductivity. At the same time, the dielectric material must have a low dielectric loss. Microtrip geometry and dimensions both can be viewed in **Figure 4.1** and **Figure 4.2** below:

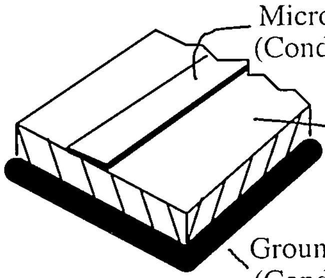

Figure 4.1: Microstrip geometry

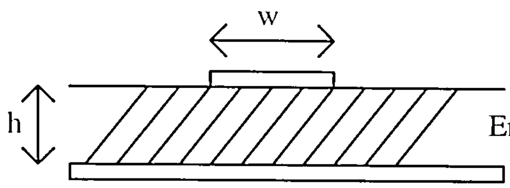

Figure 4.2: Microstrip dimensions

4.2 THE GEOMETRY OF MICROSTRIP

Microstrip geometry can be seen in **Figure 4.1**. These microstrip lines require precise geometries for accurate impedance control and good definition of coupler and filter performance. The microstrip width, w and the height, h are the most important dimensional parameters. This is followed by the relative permittivity of the substrate, ε_r . The thickness, t of the metallic, top-conducting strip is not that particular important that it is often neglected in RF and microwave applications. Nevertheless, microstrip line on-chip and on MCMs are relatively thick as a result to keep the resistance down while still achieving high wiring density by keeping the width down. Few characteristics of microstrip include the following:

- DC as well as AC signals may be transmitted.
- Active devices, diodes and transistors may readily be incorporated (shunt connections are also quite easily made).
- In-circuit characterization of devices is straightforward to implement.
- Line wavelength is reduced considerably (typically one-third) from its free-space value, because of the substrate fields. Therefore, distributed component dimensions are relatively small.
- The structure is quite rugged and can withstand moderately high voltages and power levels.

4.3 TECHNIQUE APPLIED TO MAKE BANDPASS FILTERS

Paralled-coupled microstrip technique [4] is often applied in the making of bandpass filters (BPFs) at microwave frequencies. During the design process, two or more half-wave resonators are cascaded as such to form the coupled multi-resonator BPF – each quarter-wave parallel coupled to its neighbour. This will yield a narrow-to-moderate bandwidth. To realize this filter will definitely requires the design and interconnection of two distinctly different kinds of resonant LC circuits[1]. Directly to say, both series and parallel types are needed to directly realize this filter. It is a fact that any microsrip resonators electromagnetically coupled together in some way would exhibit at least one type of resonance, make it series or parallel but not both simultaneously from similar structures. Each individual resonator will then is affected by reactive loading from adjacent couplings and open-ended capacitive fringing. Coupled transmission lines have frequency sensitive coupling and can be analyzed by the even-odd mode method.

Furthermore, figure below shows the most convenient way to construct the configuration that represents coupled $\lambda/2$ open lines.

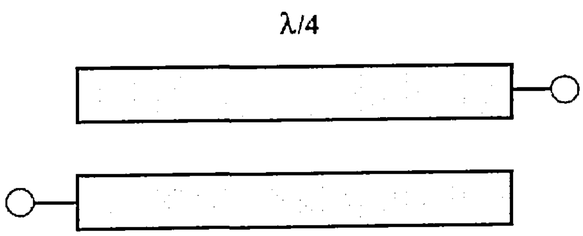

Figure 4.3: Coupled $\lambda/2$ open lines.

[1] LC circuit also know as Resonators

The equivalent circuit of two coupled $\lambda/4$ open lines can be viewed as below:

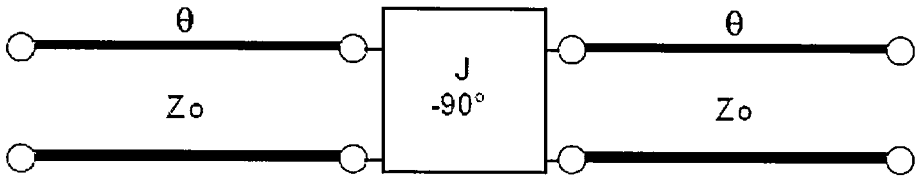

Figure 4.4: Two coupled $\lambda/4$ open lines

From there, it can be seen that a structure of a number of coupled lines will admit to an equivalent circuit of alternating series and parallel resonant circuits and the design parameters of the prototype filters can be imposed onto the structure of parallel coupled lines.

In all, there are two (2) principles, which can describe planar coupling between adjacent resonators, which are:

- End coupling
- Edge coupling

4.3.1 EDGE COUPLING (PARALLEL-COUPLED) BANDPASS FILTER

In this project, more interest is placed upon this parallel-coupled bandpass filter. It is known that, when the length of the coupled region is $\lambda_g/4$ or some odd multiple, maximum coupling will be possessed between the physically parallel microstrips. In order for resonance to occur, the length of each resonator element has to be $\lambda_g/2$ in length or any multiple thereof. Illustration of this idea can be viewed below.

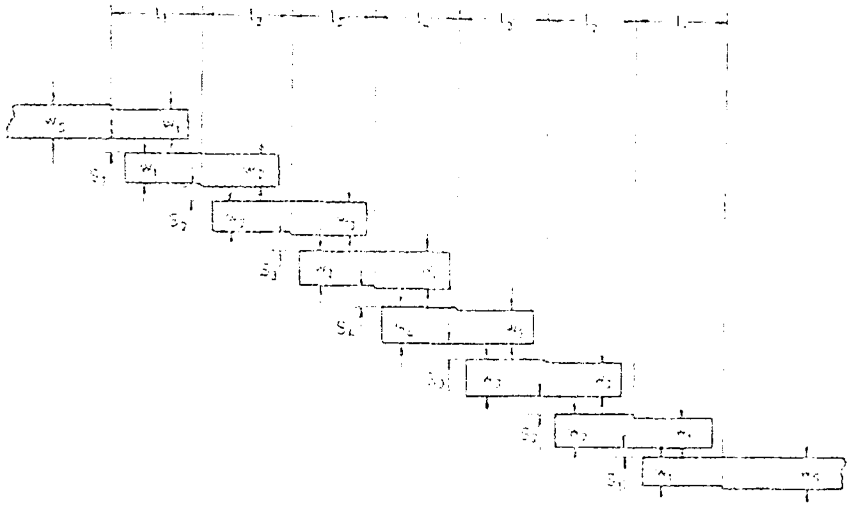

Figure 4.5: General microstrip configuration for a seven-section, parallel-coupled bandpass filter [5]

From **Figure 4.5**, $l_1,\dots\dots,l_4 \cong \lambda_g/4$. The design of the circuit come with the assumption that this fairly straightforward cascade of parallel-coupled microstrip resonators can be designed on a basis of all-parallel resonator networks together with intervening circuits known as inverters.

Therefore, in a nutshell, there are four (4) main design steps [6] for parallel-coupled bandpass filter and they are:

i. One-type resonator network will have to be determined from the original prototype.

ii. The even- and odd-ordered characteristic impedances, Z_{0e} and Z_{0o}, will then have to be evaluated from the network parameters so that they will be applicable to the parallel-coupled microstrip.

iii. Next, the values of Z_{0e} and Z_{0o} will be related to microstrip widths and separations (w,s). The procedures have been described in lengthy in Chapter 6 from [7].

iv. The last part are to calculate the whole resonator length $2l'$ to be slightly less than $\lambda_g/2$ and the coupled-section of length l' which is slightly less than $\lambda_g/4$.

λ_g in this case is the mid-band and average microstrip length. In the design process, allowance should be made for the semi-open-circuit microstrip end-effects, which exist for all elements in this circuit just as what will be discussed in **Topic 6.2.1**

In microstrip, the structure of the transmission line conductors of the coupled line filters can be observed below with the offsets between $\lambda/4$ sections added to permit seeing the individual coupled line pairs.

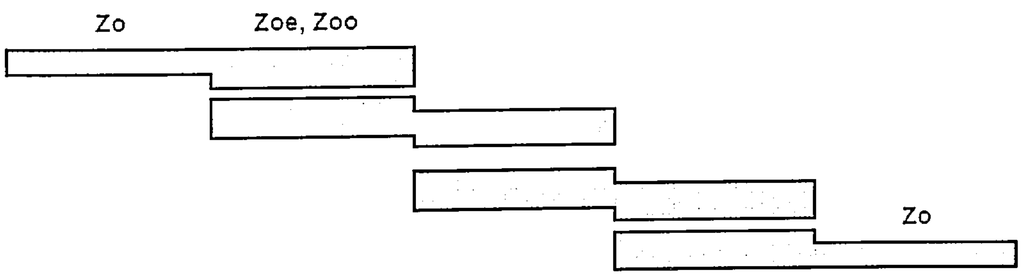

Figure 4.6: Tranmission line conductors of the coupled line filter in microstrip

The even- and odd-ordered characteristic impedances, Z_{0e} and Z_{0o} are major design parameters for any parallel-coupled transmission line configuration no matter what its application. These impedances are functions of the degree of coupling, C and the single-line terminating characteristic impedance, Z_0. The fact that Z_{0_e} and Z_{0_o} have in relation with the physical dimensions of the coupled structure are of prime importance in the design process. How this works? Equivalent to the single microstrip lines, the value of Z_{0_e} and Z_{0_o} can also be determined from the known physical dimensions, which amounts to analysis. On the other hand, the value of the physical dimensions may be extracted from the starting values of impedances but with greater difficulty of course.

The design stage of microstrip couplers requires important starting parameters to be defined at first [8] and they are:

- Coupling factor, C at the centre frequency - usually in decibels.
- Permittivity, ε_R and thickness, t of the substrate.
- Terminating characteristic impedance, Z_0 - usually 50Ω
- Bandwidth, B and centre frequency, f_0
- Coupling factor tolerance over the band – sometimes
- Lowest acceptable directivity, D in decibels.

Only then, from the information of these parameters that the designer must determine the widths of the microstrip lines, the separation between them and the length of the coupled region.

4.3.1.1 Impedance and Admittance Inverters

Analysis and design of transmission line filters can be made possible with the added tool of the impedance or admittance inverter. These transmission line networks only involve $\lambda/4$ rather than $\lambda/8$ lines [9]. It comes with the knowledge that quarter wave lines can transform series connected element to shunt element and vice versa. There also exist combinations of transmission line and lumped elements that perform the same function. In all, transmission line networks having this general property are called impedance and admittance inverters.

The quarter wave and alternative implementation of both types of inverters can be viewed in **Figure 4.7** and **Figure 4.8**

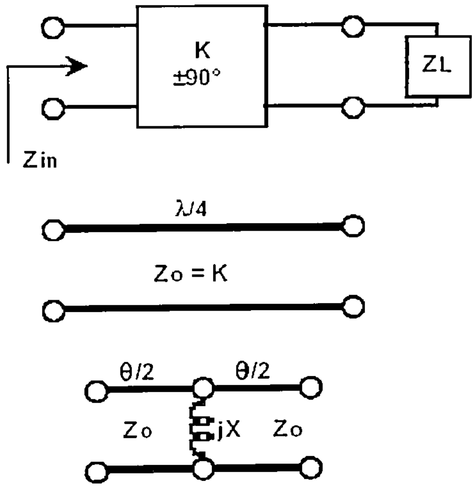

Figure 4.7: Impedance Inverters

Quarter-wave transformer takes the simplest form of an impedance inverter. Such circuit components transform any load impedance by the quantity of Z_0^2 where Z_0 is the characteristic impedance of the quarter-wave transforming section of line. The squared terms of characteristic impedance will give arise the impedance and admittance inverters.

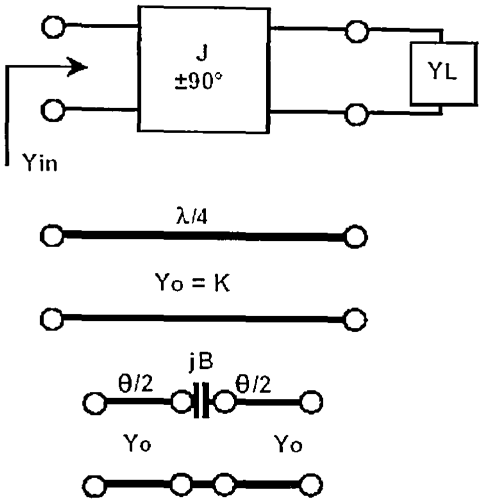

Figure 4.8: Admittance Inverters

For admittance inverters or also known as J-inverters, a network made up of this type of inverters and uniform-type resonant circuits can be made equivalent to the original network consisting of two (2) types of resonant circuit – series and parallel. The impedance level will definitely vary through the system but these two (2) features stated below must be maintained to keep the equivalence and they are:

- The resonant frequency must remain constant.

$$\omega_0^2 = 1/LC$$

- Impedances at similar planes in each network must be equal.

From **Figure 4.7**,

For the impedance inverter, $Z_{in} = K^2/Z_L$

For the 90° line, $K = Z_0$

For the lumped element implementation,

$$K = Z_0 \tan|\theta/2|$$

$$X = \frac{K}{1-(K/Z_0)^2}$$

$$\theta = -\tan^{-1}\frac{2X}{Z_0}$$

From **Figure 4.8**,

For the admittance inverter, $Y_{in} = J^2/Y_L$

For the 90°, $J = Y_0$

For the lumped element implementation,

$$J = Y_0 \tan|\theta/2|$$

$$B = \frac{J}{1-(J/Y_0)^2}$$

$$\theta = -\tan^{-1}\frac{2B}{Y_0}$$

For both cases, the transmission line lengths of $\theta/2$ are generally negative but it does not constitute a problem if the lines can be absorbed by reducing the length of connecting transmission lines on either side as can be seen in the making of filters.

4.3.1.2 Admittance Inverter Parameters, J

From **Figure 4.5**, the 'first coupling structure' that is formed by w_1, s_1, w_1 also has the same w_1, s_1, w_1 at the opposite end of the filter. The quantities 'g' refer to the prototype element values. For example, g0 = 1 and g1 = 0.781 as may be observed from the table of a sixth-order Chebyshev prototype. This is a standard data that is available in almost references. Therefore, the admittance inverter parameters, J [10] are as below:

For the first coupling structure:

$$\frac{J_{01}}{Y_0} = \sqrt{\frac{\pi\delta}{2g_0 g_1}} \tag{4.1}$$

For the intermediate coupling structures:

$$\left.\frac{J_{j,j+1}}{Y_0}\right|_{j=1to(n-1)} = \frac{\pi\delta}{2\omega_c'\sqrt{g_j g_{j+1}}} \tag{4.2}$$

For the final coupling structure:

$$\frac{J_{n,n+1}}{Y_0} = \sqrt{\frac{\pi d}{2g_n g_{n+1}}} \tag{4.3}$$

δ in these three cases is the fractional bandwidth

$$\delta = \frac{f_2 - f_1}{f_0} \tag{4.4}$$

The frequency transformation from the low-pass prototype filter to the bandpass microwave filter is then:

$$\frac{\omega_i'}{\omega_c'} = \frac{2}{\delta}\left(\frac{f_i - f_0}{f_0}\right) \tag{4.5}$$

where ω_c' : prototype cut-off frequency and equals to 1.0, and

ω_i' has to be defined in the filter specification

The last part of the design is to find the value of odd- and even-mode coupled-line impedances, Z_{0e} and Z_{0o}. The equations are given below:

For even-mode impedances, Z_{0e}

$$(Z_{0e})_{j,j+1} = Z_0(1 + aZ_0 + a^2Z_0^2) \tag{4.6}$$

For odd-mode impedances, Z_{0o}

$$(Z_{0e})_{j,j+1} = Z_0(1 + aZ_0 + a^2Z_0^2) \tag{4.7}$$

where $a = J_{j,j+1}$

Z_0 : the 'system' characteristic impedance which is the lines feeding the filter.