# Integrated Waveguide Bandpass Filters Using Thick-Film Technology

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*Abstract* - **By integrating planar circuits, such as a microstrip line, and the rectangular waveguide with inductive posts onto the same substrate, the low-loss bandpass filter can be realized without resort to tuning or mechanical mounting. However, the design and performances of the filter are limited by the conventional PCB process restrictions, such as constant via-holes diameter and material characteristics. In this paper, a single-substrate integrated waveguide bandpass filter operating in U-NII band is realized using thick-film technology.**

*Keywords* – **integrated waveguide, bandpass filter, thick-film technology.**

## I. Introduction

The wireless communications market has experienced a rapid growth in the last several years. As a result, frequency usage and commercial wireless applications have continued to move toward the millimeter wave regime. Emergence of millimeter wave wireless applications including local microwave distribution systems (LMDS, 28 GHz), WLAN (60 GHz), and automotive collision radar (77 GHz) has brought new demands for low-cost, miniaturized, high-volume packages and multi-chip modules at millimeter wave frequencies. As the level of integration and the operating frequency increase, coupling between components and parasitic reactance within the package play a greater role in the package design, resulting in new technologies for the production of microwave and millimeter-wave integrated circuits (MICs).

The significance of the Thick-film (TF) technology has been on the rise recently primarily thanks to the development of MCM, which also uses printing of conductive layers on the ceramic for interconnection of semiconductor chips. TF technology offers significant potentials for the development of microwave passive components and is capable of combining low-cost, high volume production with the high electrical performances needed for microwave devices. Recent developments in low-loss materials and photoimageable procedures, [1], made TF technology very suitable for microwave applications: typical substrate Alumina has well defined and stable relative permittivity $\varepsilon_r$ of about 9, thus significantly reducing the component size, while its high thermal conductivity results in wider operating temperature range.

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Miniature bandpass, low cost, low loss filters are necessary in mobile communications. Commonly used for those applications are ceramic block variants with a high dielectric constant of coaxial line filters in interdigital or combline form [2], dielectric filled coaxial resonators in stepped impedance form [3], etc. In mentioned variants resonator tuning was necessary after fabrication, thus making the procedure more complex. From the cost point of view, planar filters are the most preferable for mobile communications applications, but they exhibit lower quality factor values then their waveguide counterparts.

Recently, the concept of integrated rectangular waveguide embedded in the same substrate as the planar circuits has been proposed [4], showing high potentials for production of low-cost planar circuits with reduces size and weight, as well as enhancing manufacturing reputability and reliability. The proposed "artificial" waveguides were realized in conventional PCB technology, with plated rectangular via-trenches, [5], or with linear arrays of metallized via-holes serving as side walls, [6], [7]. However, the design and performances of the circuits realized in this manner were limited by the conventional PCB process restrictions, such as constant via-holes diameter and material characteristics.

In this paper, a single-substrate integrated waveguide bandpass filter using TF technology is presented. A three-pole Chebyshev filter having 0.6 dB insertion loss and return loss better than 13 dB was designed to operate in U-NII band (5.15–5.35 GHz). Thick film parameters, such as dielectric thickness, metallization thickness and paste conductivity are in accordance with those realizable by widely available standard TF procedures.

## II. Thick-Film Technology

As in the case of conventional integrated circuits, MICs can be classified by the fabrication technology into two categories:

- Film based circuits, including Thin- and Thick-film variant (hybrid MICs) and
- Monolithic ICs, incorporating bipolar or MOS technology, (MMICs).

Hybrid components also exist, combining film and monolithic technologies in a single product.

The main characteristic of a hybrid MIC is that it consists of elements inseparably associated and formed on or within a single substrate. In other words, the circuit components and all interconnections are formed as a unit.

Film technologies for fabrication of hybrid MICs are broken down into two categories, Thin-film and Thick-film (TF). Film components are made of either conductive or nonconductive material that is deposited in desired patterns on a ceramic or glass substrate. Passive circuit components, such as resistors and capacitors can be produced in this way, while active components are mounted to the substrate to complete the circuit.

In following sections, a brief overview of TF procedure, materials and fabricated components characteristics will be presented, as well as recent developments in the field.

*A. Thick-Film Procedure*

A thick film is a film of material with a thickness that is at least 10 times greater than the mean free path of an electron in that material, or approximately 10 µm. Thick films are produced by screening patterns of conducting and insulating materials on ceramic substrates. Therefore, the size and shape of patterns are arbitrary, constrained only by technology limitations. The technique is used to produce only passive elements, such as resistors and capacitors.

Thick-film manufacturing process can be divided into different stages:

- Screen printing - The substrates are screen printed with different pastes creating the conductors, resistors and dielectrics. All these tasks are made under a controlled atmosphere and using fully automatic screen printing lines.
- Firing - Firing is made at temperatures above 600°C and under a controlled atmosphere. This process forms alloys that are permanently bonded to the substrate. To a limited extent, the characteristics of the film can be controlled by the firing temperature and length of firing time.
- Laser trimming - screen printed resistors are laser trimmed to the values and tolerance specified by the customer.

These stages are repeated as many times as needed. The maximum number of layers achievable by the TF technology depends on the materials used and is typically around 8.

*B. Thick-Film Materials*

The **substrate** material must be virtually inert to the materials deposited on it except that it must provide some mechanical or chemical basis for adhesion. It must be unaffected by the firing conditions demanded by the process. Two groups of materials satisfy these demands: glasses and ceramics. Although less attractive due to its melting points, systems based on glasses or ceramic filled glasses also exist.

The most commonly used substrate material for TF integrated circuits is 96% Alumina ($Al_2O_3$). It can be obtained in a range of purities and made to accurate dimensions, while its rigidity, hardness and general physical stability add to its suitability as a substrate material. Holes are not commonly used in alumina because of the cost, although they can be either punched in or laser drilled.

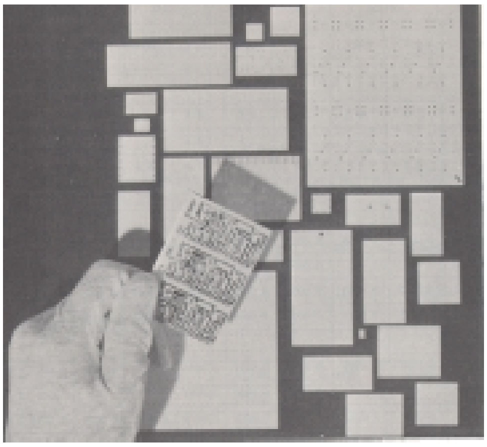

Fig. 1. Alumina is available in different sizes;
Holes can be drilled in the fabrication process (far right)

Although more expensive, 99.6% Alumina used in Thin-film technology can be applied to Thick-film, resulting in approximately 20% decrease in microwave energy loss.

Alternatives to Alumina include porcelain type glaze on steel sheets and other alloys coated with dielectric film. Aluminum nitride provides a cost-effective solution to making hybrid circuits able to withstand high thermal loads versus conventional alumina substrates.

The essential characteristics of TF **conductors** are low sheet resistance (preferably bellow 5 mΩ/sq.) and the ability to be printed in paste form. The common materials are gold (Ag) or silver (Au) either alone or in alloys with palladium (Pd) and/or platinum (Pt). Copper (Cu) can also be used, but is not process compatible with other conductors. The cost of pastes containing gold is higher, but they are normally used for fine line technology and multilayers, as they can resolve 125 µm lines on 250 µm distances. The values of the sheet resistance for typical conductor materials are given in Table I.

TABLE I
TF CONDUCTORS

| Conductor Material | Sheet resistance [mΩ/sq] |
|---|---|
| Cu | 1.5 |
| Ag / Pt | 2 |
| Au | 3 |
| Ag / Pd | 30 |
| Au / Pd | 50 |

In order to obtain the desired rang of values, TF **resistors** are composed of conductor and glass. The conductor content ranges from over 50% for sheet resistance of 1Ω/sq, to less then 5% at 1 MΩ/sq. The most commonly used conductor is ruthenium dioxide, and glasses are usually based on lead borosilicates.

The alloy materials have higher intrinsic resistivity then pure materials. This makes them unsuitable for microwave applications, thus leaving the choice of pure copper, silver and gold. The line width of 75 µm can be achieved with copper as a conductor, but the facility for copper processing has to be capable of nitrogen firing. Silver produces excellent patterns of good definition and high conductivity, but is susceptible to tarnishing, while gold, although the least conductive of the three, has the advantage of the insensitivity to atmosphere. Furthermore, the properties of gold pastes are very controllable, making the fabrication of smooth and sharp-edged patterns easier. This is counterbalanced by the very high cost.

**Dielectrics** used in thick-film have to be compatible with the conductors between which they are sandwiched. There are two main categories of dielectrics used, namely crystallizing glasses (glass ceramics) and ceramic filled glasses. If the filler for the glass is titanate, higher permitivity dielectrics are produced, suitable for use in capacitors. The glass ceramics were introduced to maintain dimensional stability when multiple firing was necessary, but now they have two roles. The first is to provide wetting for the glass and the second is for part of it to dissolve in the glass and raise its melting point, increasing viscosity.

Generally, the designer is presented with the choice of high-temperature, noble metal vs. low-temperature, polymer pastes materials (not to mention the medium-temperature porcelain/steel substrate and base-metal approach). While the first offers excellent performances, the second is less expensive. However, the reduced performances offered by the low-cost polymer approach are still acceptable in many consumer and professional applications.

### *C. Limitations and High-Frequency Consideration*

At microwave frequencies, practical limitations are imposed by TF technology. Alumina, the most often employed TF substrate, can not be used above 40 GHz, due to high losses introduced. For example, a 50-Ohm microstrip line over a typical 625 um high Alumina with dielectric constant 9.6 and dielectric loss tangent 0.004, exhibits approx. 0.5 dB insertion loss at 30 GHz, going as high as 0.7 dB at 40 GHz.

Another limitation is minimal line width and spacing which for standard TF procedure equal to 200 um. This width corresponds to line impedance of around 75 Ohm. Lines of higher impedance are difficult to obtain without resorting to modified techniques such as photoimageable procedure. Spacings equal to 200 um are often not adequate, since stronger coupling between lines may be required. In that case, one must choose multilayer design since lines in adjacent layers will be separated only by a single dielectric layer, typically 20 um thick.

### *D. Photoimageable Procedure*

Recently new photoimageable procedures were reported [1], allowing fabrication of fine pattern geometry and lines with stable width, comparable to those obtained by the thin-film technology. The proposed technique is a combination of conventional TF technology and some processes typical for thin-films. Firstly, the coating layer of photosensitive paste is deposited on the substrate, leveled and dried at the temperature of 80°C. After drying this layer is exposed to UV light through the negative photo mask and then developed, thus removing the undesired amount of paste, Fig. 2. The pattern that remained is fired in a conventional TF furnace.

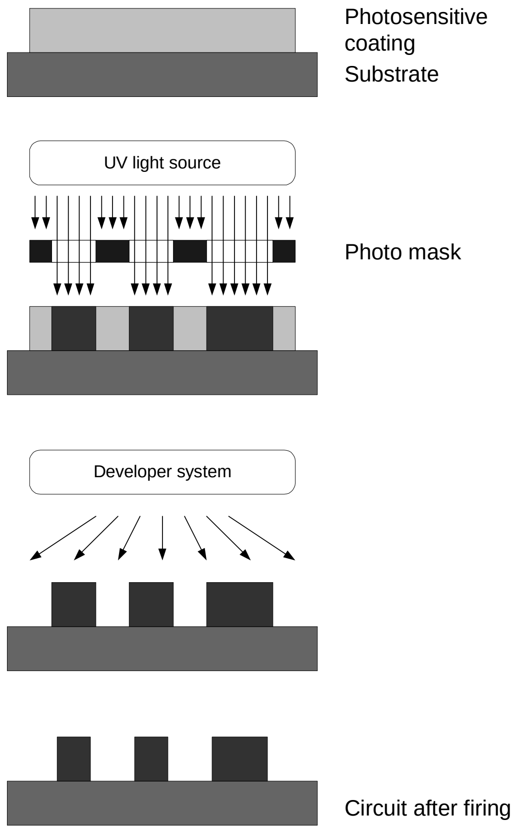


Fig. 2. Steps in photoimageable TF fabrication process

The major enhancement introduced by the photoimageable TF procedure is that the printing step and pattern generation step are separated and independently optimized. In this manner, lines and spacings of 50 um can be fabricated with ±5 um tolerance and smooth, well defined, near-vertical edge features.

### *E. Summary of the Thick-Film Technology*

Thick-film technology using standard printing process allows for line widths and spaces above 200 μm to be produced. The resultant print thickness is in the range of 8-12 μm. Line width and spaces below 100 μm are very difficult to obtain, since lines tend to be irregular with globulation and open circuits. The exact limits of printing depend on paste type, rheological system, type of screen used etc.

Another drawback is that while it is possible to achieve minimum dimensions repeatedly in a first printing on the substrate, such may not be the case with later printings. Thus, in a multilayer structure, components with critical dimensions should be printed as early as possible and directly onto the substrate.

Thick-film has a considerable cost advantage over thin-film. Apart from this, advantages of TF technology include:

- Possibility to set up arbitrary values of resistors with the accuracy of up to 0.2%,
- High thermal conductivity of the substrate resulting in wider operating temperature range,
- Possibility to create 4 conductive layers with low production costs,
- High tolerance to temperature, moisture, vibrations and heat build up.

Thick-film technology offers a high level of integration at low costs, and is very suitable for production of custom circuits. In addition to circuit size and weight reductions over standard PCB packaging, it simplifies assembly and offers improvements in circuit performances, achieved by shortened circuit paths and closer spacing that yield reduced noise pickup, enhanced thermal coupling, and improved stability.

Finally, thick-film is conceptually a simple process which can be semi or fully automated, so the production facilities established range from inexpensive semi-manual through to fully automated ones.

## III. INTEGRATED WAVEGUIDE BANDPASS FILTER CONFIGURATIOPN

Rectangular waveguides can be used to design high-Q components such as resonators and filters, but require complex transitions to planar integrated circuits. Such transitions can be fabricated using high-precision mechanical processes which are unsuitable for mass production of circuits working in the millimeter-wave frequency range. The final circuit becomes voluminous, requires accurate assembly and tuning, thus making the waveguide integration difficult and expensive.

A straightforward solution proposed in [6] and [7], is integration of the rectangular waveguide directly into the microstrip substrate. Since the propagation constant of the $TE_{10}$ mode is only related to the waveguide width *a*, the height of the waveguide *b* can be reduced to (maximum) dielectric layer thickness. As a result, losses will be increased and Q-factor lowered, but the entire circuit will be planar in nature, thus allowing straightforward fabrication using standard PCB or other planar processing techniques.

In this Section integrated waveguide bandpass filter is presented realized in TF technology.

The configuration of the proposed bandpass filter is shown in Fig.3. Input and output 50-Ohm microstrip lines and the integrated waveguide are oriented along the same axis. The transition is formed with the simple matching geometry between both structures, a tapered microstrip line, optimized to minimize the return loss and the taper length. The waveguide side walls can be realized as completely metallized or metallic post arrays. The first approach was accepted since it introduces lower insertion loss then the second one. The fabrication of complete metallized side walls does not present an obstacle in the TF technology as might be the case in standard PBC processes, since the top layer conductor paste can be deposited in slightly wider pattern then the conductor, thus allowing the paste to pour down the both sides.

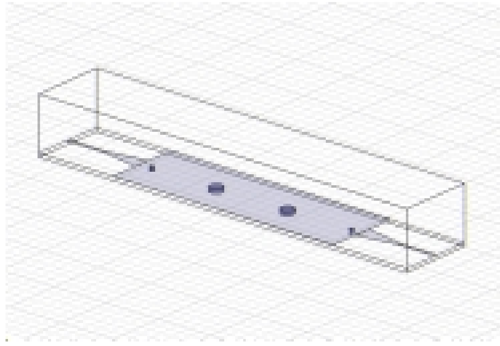

Fig. 3. Bandpass filter configuration

The circuit is constructed on an *H*=625 um thick dielectric substrate Alumina with dielectric constant $\varepsilon_r$=9.6. The filter is realized as a waveguide with complete metallized side walls and a centered array of inductive posts. The bottom side of the waveguide is ground layer formed on the bottom substrate side. Top waveguide side is fabricated as a TF conductive layer deposited on the substrate. Side walls are realized as explained above. The height of the waveguide equals to the substrate height, *H*. Top view of the filter is shown in Fig. 4, while the corresponding dimensions are given in Table II.

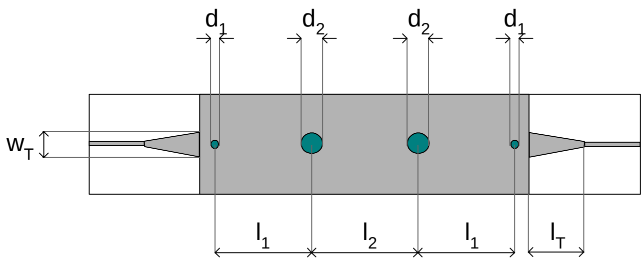


Fig. 4. Top view of the filter with dimensions referring to Table I.

TABLE II
DIMENSIONS OF THE FILTER ELEMENTS

| | |
|---|---|
| **50 Ω - MICROSTRIP LINE** | |
| Width, $w_{MS}$ | 0.608 mm |
| **TAPER** | |
| Width, $w_T$ | 3 mm |
| Length, $l_T$ | 7 mm |
| **INTEGRATED WAVEGUIDE** | |
| Width, *a* | 12.954 mm |
| Height, *b* | 0.625 mm |
| Length, $l_1$ | 12.2 mm |
| Length, $l_2$ | 13.55 mm |
| Diameter, $d_1$ | 0.76 mm |
| Diameter, $d_2$ | 2,28 mm |

The filter is designed to operate in U-NII band (5.15-5.35 GHz), as a three-pole Chebyshev filter, using standard design procedures presented in [8]. Thick film parameters, such as dielectric thickness, metallization thickness and paste conductivity are in accordance with those realizable by widely available standard TF procedures.

## IV. Simulation Results

Filter performances were determined by full-wave finite-element method simulations with a commercially available software package Ansoft HFSS ver. 8.5. Fig. 5 shows return and insertion losses for the proposed filter.

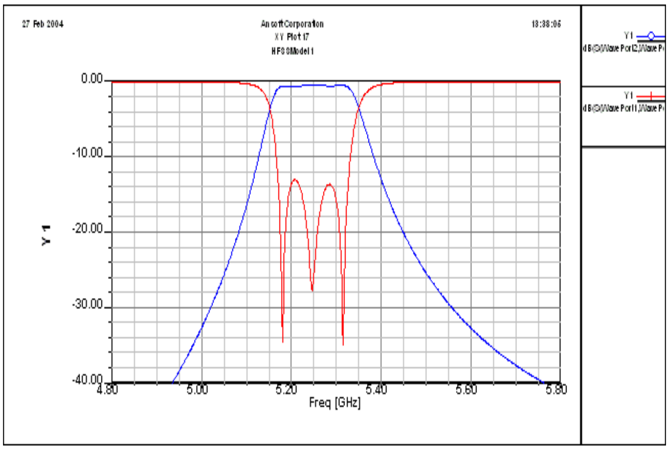


Fig. 5. Simulated results for the integrated waveguide bandpass filter

The obtained return loss is better than 13 dB over the whole frequency range of interest. The enlarged detail, shown in Fig. 6, illustrates low passband ripple factor which is below than 0.6 dB over the whole passband region.

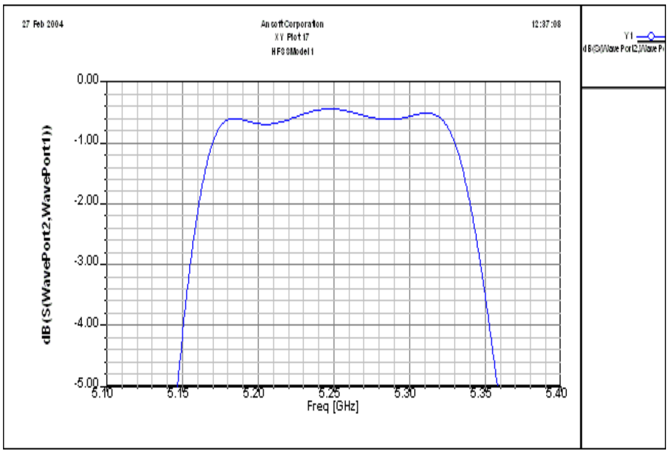


Fig. 6. Simulated results – passband detail showing low passband ripple

## V. Conclusion

In this paper a single-substrate integrated waveguide bandpass filter with centered array of inductive posts and complete metallized side walls using Thick-film technology has been presented. The performances of the filter were investigated using full-wave electromagnetic simulations. Obtained results proved that direct integration, small size and low loss characteristics achieved by the single-substrate integration technique can be preserved by the use of TF technology.

Integrated waveguides presented in the literature to date were fabricated using the conventional printed circuit technique. The design and performances of those circuits were limited by the conventional PCB process restrictions, such as constant via-holes diameter and given material characteristics. Furthermore, waveguide side walls had to be fabricated as arrays of metallized vias, thus introducing additional insertion loss. By the use of TF technology these restrictions are overcome. Complete metallized side walls can be fabricated, as well as metallic posts of arbitrary diameter. Conductor and dielectric materials can be chosen by the designer to suit the specifications and further improve the performances of the circuit.

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