Design and Fabrication of Substrate-Integrated Waveguide (SIW) Filters Using LTCC

By:

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Research Focus

Proposed Title

Design and Fabrication of Substrate-Integrated Waveguide (SIW) Filters Using Low Temperature Co-fired Ceramic (LTCC)

Main Advisor: Prof. Aicha Elshabini, IEEE & IMAPS Fellow
Co-Advisor: Prof. Fred Barlow, IEEE Senior & IMAPS Fellow

Major Technical Contributions

New methodology for design waveguide filters embedded in Low Temperature Co-fired Ceramic (LTCC) substrate
Problem Formulation

- Introduce a new methodology of designing waveguide inductive strip filters embedded in Low Temperature Co-fired Ceramic (LTCC)

- The design method of the filter was derived by applying the equivalent T-network of the inductive strip derived using the ‘Variation Principle’ to the usual technique of the filter design

- Three-dimensional electromagnetic field modeling and simulation was carried out using HFSS (High Frequency Structure Simulator)

- Fabrication of the designed filters using 9k7 and 951 green-tapes LTCC
• An example of a 4th order, maximally flat band pass filter in Ku-band is presented in this work using 9K7 green-tape

• Another example of a 4th order, maximally flat band pass filter in V-band is presented using Air-filled Substrate-Integrated Waveguide (SIW) embedded in 951 green-tape

• A comparison between various types of embedded waveguide structures
## Research Focus
- Why Waveguide Filters!!!!
- LTCC Technology

## Why Waveguide Filters!!!!

### Advantages
- Capability of high power transmission
- A non-radiating structure
- Thermal efficiency

### Disadvantages
- Complicated structure
- High cost
- Hard to mass produce
- Large size
- Difficulty of excitation

**Solution:** Embedding a waveguide filter in an LTCC substrate
Low Temperature Co-fired Ceramic Technology (LTCC)

- LTCC technology involves the production of multilayer circuits from ceramic substrate tapes or sheets
- Conductive, dielectric, and resistive pastes are applied on each sheet or tape as needed, and then the sheets are laminated-together and fired in one step according to specified firing profile
- The interconnection between components in different layers is achieved using conducting Via holes
- Since firing takes place at low temperature, typically about +850 °C, high conductivity conductor materials such as silver and gold can be used with LTCC system
Electronic Packaging at the University of Idaho

- Principal focus of Idaho Microelectronics Laboratory (IML)
  - Electronic packaging & back end processes
  - Integration of passive components
  - Assembly
  - Substrate design, simulation, and fabrication
  - Package reliability testing

Spectroscopy, Testing, and Package Reliability
Power, High Frequency, and Extreme Environment Packaging
Low Temperature Co-fired Ceramics (LTCC), Thick Films, Advanced Polymers, Thin Films

Integrated Passive Components
Package Assembly
Electrical and Mechanical Design and Simulation

http://www.IML.uidaho.edu
Integrated Passives

Substrate is x,y interconnects and insulation.

Substrate is x,y interconnects and insulation, plus integrated passives, possibly requiring extra layers.
Microelectronics & Electronic Packaging

Courtesy of HiDEC, University of Arkansas
Why Waveguide Filters!!!!!

LTCC Technology

Design Methodology

- Process Flow

**LTCC Process Flow**

1. **Unroll & Precondition**
2. **Blanking**
3. **Via Punching**
4. **Via Filling**

**Post Firing Processes**

- **Firing**
- **Lamination**
- **Stacking**
- **Screen Printing**

- Pressure ~ 3000 psi
- Temp = 70°C
• Why Waveguide Filters!!!!!
• LTCC Technology
• Design Methodology

- Process Flow

Picture from: http://mwrf.com/Articles/ArticleID/12732/12732.html
Benefits of LTCC Technology

• More economical manufacturing process compared with the conventional thick film technology

• Mass production methods can be really applied

• Fabrication techniques are relatively simple and inexpensive

• Due to the possibility to burying (hiding) passive components within the substrate, the technology reduces the size of circuits (down to about 50 percent in comparison to the PCB)

• Ability to perform at high frequencies

• High resistance against ambient working temperatures (up to 350°C)

• Good thermal conductivity compared to PCBs and Thin Film Depositions
**Idea/Concept**

Embedding a waveguide filter in an LTCC substrate is one solution that makes the waveguide filters successful in microelectronic applications and hence the name, Substrate-Integrated Waveguide (SIW)

The disadvantages of the conventional waveguide filters are eliminated using LTCC technology

The cost will typically be lower, it can easily be mass produced, and these designs can also be tested reasonably
Design Methodology

**Equivalent T-Network**

The geometry of metallic strip placed in the middle of a waveguide parallel to the E-plane.
(left figure shows end-view and right figure shows top-view)
Using the Z-parameter equivalent circuit, the T-network can be obtained as shown:

\[ Z_S = jX_S \]

\[ Z_P = jX_P \]
The T-network can be redrawn to become a symmetrical network, as shown

For one half circuit:
- The open circuit impedance is $Z_{O.C} = Z_{11} + Z_{12}$
- The short circuit impedance is $Z_{S.C} = Z_{11} - Z_{12}$

The open circuit boundary is equivalent to a magnetic wall at ($Z = W/2$), and the short circuit boundary is equivalent to an electric wall.
For one half circuit:
- The open circuit impedance is \( Z_{O.C.} = Z_{11} + Z_{12} \)
- The short circuit impedance is \( Z_{S.C.} = Z_{11} - Z_{12} \)

For the T-network:
- \( jX_S = Z_S = Z_{S.C.} \)
- \( jX_P = Z_P = \frac{1}{2}[Z_{O.C.} - Z_{S.C.}] \)

*The expressions of \( Z_{O.C.} \) and \( Z_{S.C.} \) for one half circuit can be obtained using the Variation Principle*
Variation Principle

Since the discontinuity in the waveguide due to the inductive strip is uniform along the y-axis, the only types of higher order modes excited at the strip are $H_{n0}$ modes.

The field in the region $Z \leq 0$ will be given by an expansion in terms of an infinite set of $H_{n0}$ modes as follows:

$$E_y = a_1 \phi_1 e^{-\Gamma_1 Z} + R_1 a_1 \phi_1 e^{\Gamma_1 Z} + \sum_{n=3,5,\ldots}^{\infty} a_n \phi_n e^{\Gamma_n Z}$$

$$H_x = -Y_1 a_1 \phi_1 e^{-\Gamma_1 Z} + R_1 Y_1 a_1 \phi_1 e^{\Gamma_1 Z} + \sum_{n=3,5,\ldots}^{\infty} Y_n a_n \phi_n e^{\Gamma_n Z}$$

Where,

$$\phi_n = \sin\left(\frac{n\pi x}{a}\right)$$

$$\Gamma_n^2 = \left(\frac{n\pi}{a}\right)^2 - k_0^2$$

$$Y_n = \frac{-j\Gamma_n}{k_0} Y_0$$

$$k_0 = \frac{2\pi}{\lambda_0} \equiv \text{free space wave number}$$

$$Y_0 = \frac{1}{\eta_0} \equiv \text{characteristic admittance of free space}$$

$$R_1 \equiv \text{reflection coefficient}$$
For the case of magnetic wall, at \( Z=W/2 \) the transverse magnetic field vanishes. Thus, the expression of the field in the region \( 0\leq Z\leq W/2 \) will be as follows:

\[
E_y = \sum_{n=1,3,\ldots}^{\infty} b_n \psi_n(x) \cosh \gamma_n (Z - \frac{W}{2})
\]

\[
H_x = \sum_{n=1,3,\ldots}^{\infty} Y_{0n} b_n \psi_n(x) \sinh \gamma_n (Z - \frac{W}{2})
\]

Where,

\[
\psi_n(x) = \sin \left(\frac{2n\pi x}{a - t}\right)
\]

\[
\gamma_n^2 = \left(\frac{2n\pi}{a - t}\right)^2 - k_0^2
\]

\[
Y_{0n} = \frac{-j\gamma_n}{k_0} Y_0
\]

\[
k_0 = \frac{2\pi}{\lambda_0} \equiv \text{free space wave number}
\]

\[
Y_0 = \frac{1}{\eta_0} \equiv \text{characteristic admittance of free space}
\]
Applying the continuity of the transverse fields at $Z = 0$ and then the Fourier analysis expansion, a variational expression for $Z_{o,c}$ can be obtained as follows:

$$
(Z_{o,c})^{-1} = \frac{-j \int_0^a \varepsilon(x)\varepsilon(x')G_1(x|x')dx dx'}{\left[\int_0^a \varepsilon(x)\phi_1(x)dx\right]^2}
$$

For the case of electric wall, at $Z = W/2$ the transverse electric field vanishes. A similar procedure like the magnetic wall can be done, and gives the following variational expression for $Z_{s,c}$:

$$
(Z_{s,c})^{-1} = \frac{-j \int_0^a \varepsilon(x)\varepsilon(x')G_2(x|x')dx dx'}{\left[\int_0^a \varepsilon(x)\phi_1(x)dx\right]^2}
$$
A convenient choice for the transverse electric field $\varepsilon(x)$ is to be an expansion in terms of the orthogonal set of functions $\psi_m(x)$ as follows:

$$
\varepsilon(x) = \sum_{m=1,3,..}^{M} b_m \psi_m(x)
$$

The parameter $M$ is chosen according to the accuracy required. The results obtained from the design example show that a two-term approximation is sufficient for the determination of the $Z$-parameters.
Using the two-term expansion of the electric field, the evaluation of $Z_{O.C.}$ reduces to the evaluation of $(2x2)$-determinants equation as follows:

$$(Z_{O.C.})^{-1} = \begin{vmatrix} 1 & h_{31} & \frac{1}{p_{11}p_{31}} \hline \frac{h_{11}}{p_{11}} & \frac{h_{33}}{p_{31}} & \frac{h_{13}}{p_{11}p_{31}} \end{vmatrix} = -j \begin{vmatrix} \frac{h_{11}}{p_{11}^2} & \frac{h_{13}}{p_{11}p_{31}} \hline \frac{h_{31}}{p_{31}} & \frac{h_{11}}{p_{11}^2} & \frac{h_{33}}{p_{31}} & \frac{h_{13}}{p_{11}p_{31}} \end{vmatrix}$$

Similar equation is valid for the calculation of $Z_{S,C.}$

By selecting the desired working frequency, the waveguide width, and the inductive strip thickness, these equations establish a relation between the strip width (W) and the T-network parameters (Xp and Xs), which can be given in a curve-format using a MATLAB-program

Curves are shown in the design example for a 4th order maximally flat Band Pass Filter (BPF) in the Ku-frequency band
Band-Pass Filter Design

Geometry of \( n^{th} \) Order Waveguide Inductive Strip Band Pass Filter

T-equivalent network of \( n^{th} \) Order Waveguide Inductive Strip Band Pass Filter
The design method of the filter was derived by applying the equivalent circuit of the inductive strip to the usual method of filter design using K-inverters.

The relationship between the K-inverter values and the T-reactance values (Xp and Xs) is given as follows:

\[ K_{j-1,j} = \left| \tan\left(\frac{1}{2} \phi_j + \tan^{-1} X_{sj}\right) \right| \]

\[ \phi_j = -\tan^{-1}(2X_{pj} + X_{sj}) - \tan^{-1} X_{sj} \]

\[ \theta_j = \pi + \frac{1}{2} (\phi_j + \phi_{j+1}) \]

An iterative technique can be built to get the value of the strip width (W) associated with each K-inverter value and the spacing between the strips is given by:

\[ L_j = \frac{\theta_j}{2\pi} \lambda_g \]
**Design Example**

**Filter Specifications:**

- 4\(^{th}\) order maximally flat

- Ku-band pass filter with center frequency of 14 GHz

- Fractional bandwidth of 3%

- 9K7 green-tape LTCC substrate with dielectric constant of 7.1 and tangent loss of 0.001 at 14 GHz

- Embedded waveguide width of 5.92 mm and height of 3 mm

- Strip thickness of 0.2 mm
Design Outcomes

Applying the Variation principle along with a MATLAB program, two curves that relate the strip width (W) to the T-reactance parameters (Xs) and (Xp) were generated.
An iterative process was built along with the MATLAB results. The strip widths and spacing were obtained

\[
\begin{align*}
W_1 &= 0.355 \text{ mm} = W_5 \\
W_2 &= 2.318 \text{ mm} = W_4 \\
W_3 &= 2.889 \text{ mm} \\
L_1 &= 4.04 \text{ mm} = L_4 \\
L_2 &= 4.098 \text{ mm} = L_3
\end{align*}
\]

Due to the fringing effect around the strip edges, the strips appear to be wider than their original widths.

A reduction factor must be added to the values of the strip widths and a corresponding expansion factor will be added to the spacing between the strips.
Simulation and Results

Simulation Details:

- High Frequency Structure Simulator (HFSS) was used to model and simulate the designed filter
- A grounded coplanar waveguide (GCPW) was used as the excitation ports of the filter
- A total of 17 green-tape layers were used
  - Two layers for the GCPW
  - 15 layers for the embedded waveguide
- The actual length of the embedded waveguide was 1.575 inches and the actual width was 0.233 inches
- All via holes are 10 mil in diameter
The simulation was made using various types of embedded waveguide by changing the waveguide wall structure as:

- Solid metallic-wall
• One row via holes with 10 mil diameter and spacing less than one tenth of the guided wavelength
• One row via holes along with a metal trace connecting them for each green tape layer
- Two rows via holes with 10 mil diameter and staggered with spacing less than one tenth of the guided wavelength
Two rows via holes staggered along with metal trace connecting them for each green tape layer.
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Simulation Details

Results
Current Project

Problem Formulation

Conventional LTCC green-tape (such as 951) has the advantage of low cost and ease of fabrication but it has a limitation for use in high frequencies due to its relatively high loss tangent when compared to low loss LTCC green-tape (such as 9k7)

A new method of using the cheap conventional LTCC green tape, such as 951 green-tape in V-band is introduced
**Design Idea**

Using **Air-filled Substrate-Integrated Waveguide** (SIW) filters are one solution that makes the waveguide filters successful in high frequency microelectronic applications using conventional green tape (such as 951 green-tape)

The conventional green tape was used as a **support** to the metallic strips, the via holes, the excitation probe, and the outer filter structure

**Still under simulation and optimization**
Publications


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QUESTIONS

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