Lightweight Filter Technology for UAV and Satellite Applications

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Abstract: *This paper presents high performance, robust, substrate integrated waveguide (SIW), bandpass filters operating in the microwave and millimeter-wave frequency range. These filters are significantly smaller (50x) and lighter (100x) than conventional metal waveguide technology while maintaining unloaded quality factors > 500. A precision batch manufacturing process has been developed enabling these filters to be produced at lower costs without the need for post-fabrication tuning.*

Keywords: Bandpass filter; Substrate integrated waveguide; High Q.

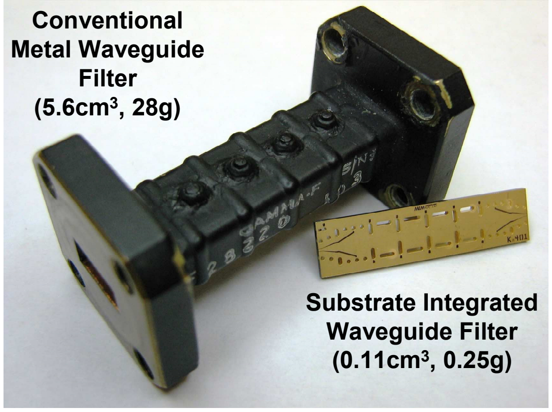

Figure 1. A substrate integrated waveguide filter can be 100x lighter and 50x smaller than conventional metal waveguide filters.

Introduction

High performance bandpass filters play a crucial role in many types of communication systems. The conventional metal waveguide filter is the de facto standard for high performance applications, but their large size, weight, and volume manufacturing costs preclude their use in many applications. Bandpass filters for unmanned air vehicles (UAV), satellite communications, and phased array antenna applications, where size and weight are a premium demand a unique solution.

Substrate integrated waveguide (SIW) has received much attention over the past decade due to its low cost, small size, integration potential and superior performance over alternative planar filter technologies (microstrip and stripline). SIW, as first proposed in [1], is a dielectrically-filled waveguide transmission line formed using printed circuit board (PCB) processing of a substrate material. Metal planes on the top and bottom surfaces of the substrate are electrically connected using two parallel sets of collinearly-arranged metal-plated via holes. These via patterns function as the waveguide sidewalls. The resultant structure is essentially a rectangular waveguide whose modes and propagation characteristics are the same as their traditional, metal waveguide counterparts.

Despite the desirable characteristics of SIW filters, their integration into fielded systems is not widespread. To date, majority of the SIW filter demonstrations have made use of high-frequency laminates combined with standard PCB processing [2,3] or low-temperature cofired ceramic (LTCC) processes [4,5], both of which lack the necessary precision to repeatedly and reliably manufacture high performance bandpass filters. The relatively low tolerances of PCB processes and the shrinkage of LTCC constructions during the firing process limit the accuracy with which these processes can fabricate filters. This limits their ability to meet the demanding requirements of present day filter designs. Additionally, the materials used in these processes do not present the absolute lowest loss or the most desirable operational characteristics due to their dielectric loss tangents (tanδ), coefficients of thermal expansion (CTE), and temperature coefficients of permittivity (TCP). Table 1 compares the pertinent material characteristics for the most common materials used in these processes and the selected material used for the filter technology presented in this paper. Note, the parameters listed in Table 1 reflect measurements taken at 1 MHz.

Table 1. Material parameters for common substrates used in the construction of SIW filters and fused silica.

Material	ε_r@ 23°C	TCP (ppm/°C)	tanδ	CTE (ppm/°C)
RT/Duroid 5880 [6]	2.2	-125	0.0004	31-48
Dupont 951 LTCC [7,8]	7.8	-80	0.006	5.8
Fused Silica [This work]	**3.8**	**≤ 9**	**0.000015**	**0.5**

The filter technology presented within this paper adapts precision thin-film circuit processing to create SIW filters from low-loss fused silica wafers. These filters help unlock the potential of SIW technology and provide new advantages for military systems where there are strict limitations in cost, size, or weight. Specifically:

- 50x smaller volume, 100x lighter weight than traditional metal waveguide filters;
- Batch fabrication of filters for lower cost, no post-fabrication alignment required;
- Quality factors ranging from 500 to 1000 depending on frequency and size;
- Coplanar input/outputs for direct wafer probing, wire bondable for easy assembly;
- Operates over full military temperature range, no compensation required for most applications.

Design

As an example of the potential of this platform, a four-pole, Ka-band filter was designed, fabricated, and tested. The filter design parameters of this demonstration vehicle are as shown in Table 2.

Table 2. Desired performance values for a Ka-band fixed filter demonstration vehicle.

Parameter	Value
Center Frequency	36.2 GHz
Bandwidth	0.55 GHz
Return Loss	> 16 dB
Filter Poles	4

The filter was designed to have a waveguide width of 2.946 mm and height of 0.762mm. The dielectric permittivity is 3.825, which provides a waveguide cutoff frequency of approximately 26 GHz. In this media, the wavelength in waveguide is 6.345 mm with an impedance of 283 ohms. With a metal resistivity of 1.4x that of bulk gold and a dielectric loss tangent of 0.00033 (@ 36.2 GHz), the quality factor of the guide itself is estimated to be in the range of 800-1000. The impact of the transition losses must also be considered, reducing the “effective” quality factor of the overall filter.

To achieve the desired filter performance shown Table 2, a filter was developed which possessed a four-pole, 0.1 dB Chebyshev bandpass filter response. The initial schematic of this filter is shown in Figure 2. The values for the inverters help define the dimensions of inductive irises between each of the waveguide resonators. The length of the individual waveguide resonators is just over 3mm long (these dimensions must be modified to absorb the excess phase shift exhibited by the iris inverters).

Construction

This filter was fabricated in a commercial thin-film facility using high precision semiconductor-based batch fabrication methods. Filter construction consists of creating laser machined via slots in 0.762 mm thick fused silica wafers to define waveguide sidewalls and coupling elements between resonators. These via slots are manufactured with micron accuracy. After the geometries of the sidewalls and coupling elements have been created, a metal seed layer is sputter deposited. Then, photoresist is patterned and etched to define the coplanar waveguide (CPW) input and output transitions. Next, approximately 4 μm of gold is electroplated onto the top and bottom surfaces and the sidewalls of the vias. In this design, tapered transitions are utilized to provide a broadband transition between CPW ports and the waveguide interior.

Performance

Figure 3. Ka-band substrate integrated filter developed as a demonstration platform for tunable filters.

An example 4-pole bandpass filter built using this technology is shown in Figure 3. Figure 4 shows the insertion loss response of 12 filters fabricated on the same wafer. There are no provisions for tuning these filters; this response is “as manufactured.” The filter center frequency is 36.2 GHz with a 550 MHz ripple bandwidth. The standard deviation of the filter center frequency is 38 MHz, or about 0.11% of the center frequency. Filters from other wafers and fabrication runs have exhibited similar uniformity. The filter has a mid-band insertion loss of 2.6 dB with a standard deviation of less than 0.05 dB. This loss is equivalent to an average unloaded quality factor of 550. The filter dimensions are 24.4mm x 5.9mm x 0.76mm while the weight is a miniscule 0.25 grams. Out of band

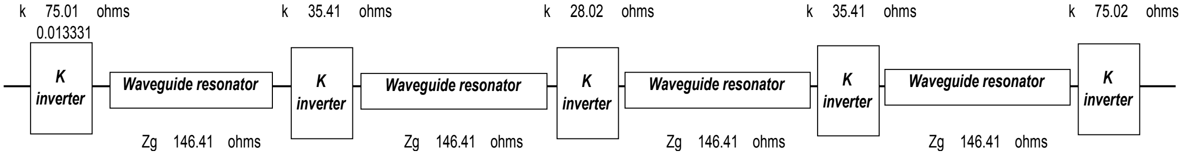

Figure 2. Schematic of 4-pole, 0.1 dB Chebyshev filter designed as a filter platform test vehicle.

rejection is better than 25 dB down at one ripple bandwidth away, with a broader rejection of > 40 dB farther away from the center frequency.

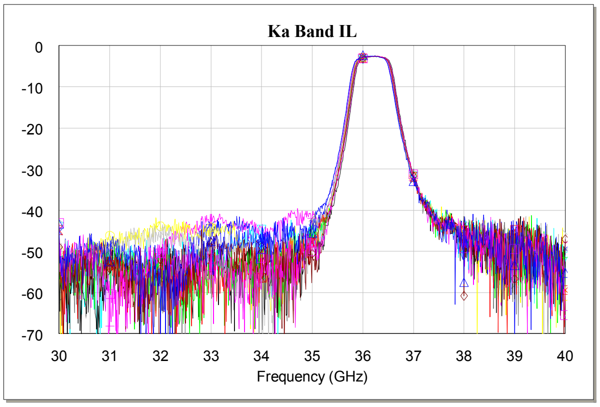

Figure 4. Twelve Ka-band SIW filters fabricated on the same wafer exhibit a variation in center freq of 0.11 %.

Figure 5 demonstrates the insertion loss and return loss of a typical filter over the 25°C to 150°C temperature range. The total variation in filter center frequency over this range is -29 MHz. This is generally in line with prior measurements of these filters over temperature, varying by approximately -6 ppm/°C to -9 ppm/°C. This variation is theorized to be caused by variation in the dielectric constant of the fused silica substrate rather than mechanical expansion or contraction of the filter body (which is only 0.5 ppm/°C for the fused silica substrate). For many applications, this variation does not require compensation, and can be taken into account when determining the bandwidth and required number of poles necessary to achieve a desired filter rejection.

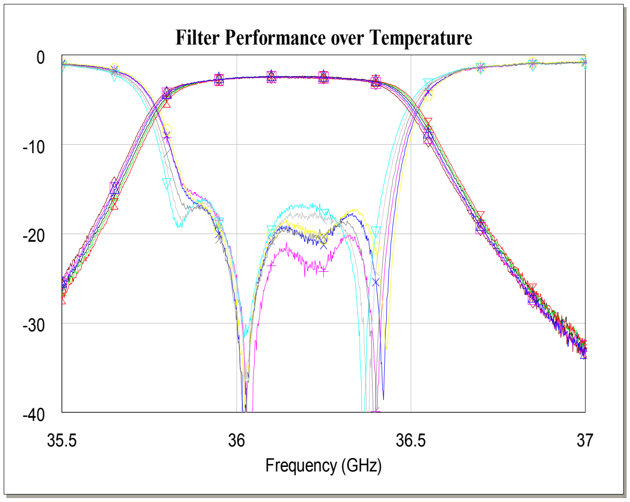

Figure 5. Ka-band SIW filter performance over 25°C - 150°C temperature range.

Conclusion

A precision manufacturing technology has been developed which creates high performance bandpass filters in the microwave and millimeter-wave frequency range that are significantly smaller and lighter than conventional metal waveguide technology. As these filters are manufactured in a semiconductor manufacturing environment, precision fabrication and batch manufacturing processes enable these filters to be produced at lower costs without the need for manual post-fabrication alignment.

The demonstration vehicle, a 4-pole Ka-band SIW bandpass filter constructed from a fused silica wafer, illustrated the excellent reproducibility and accuracy with which this process affords. These characteristics are a significant improvement over the current state-of-the-art for SIW filters. In addition, the use of fused silica as the base material means these filters have lower dielectric losses and better performance over temperature than SIW filters constructed from high-frequency laminates or LTCC.

This technology is applicable to bandpass filters for UAV and satellite applications which require unloaded quality factors > 500, operating frequencies in the 2 GHz – 50+ GHz range, two to eleven filter poles, and where size and weight is at an absolute premium.

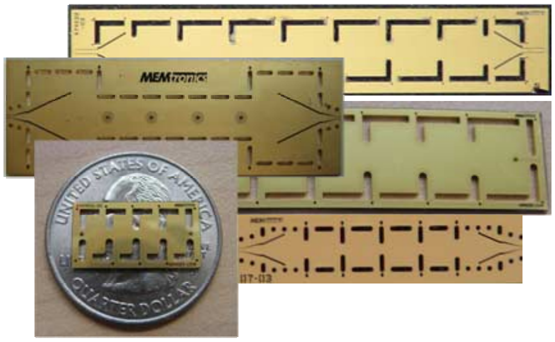

Figure 6. Precision fabricated SIW filter technology offers significant advantages from X-band to Ka-band.

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