LIGA Micromachined Planar Transmission Lines and Filters

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***Abstract*— This paper introduces a new class of three-dimensional (3-D) micromachined microwave and millimeter-wave planar transmission lines and filters. The LIGA process allows tall (10 μm–1 mm), high-aspect ratio metal structures to be very accurately patterned and is compatible with integrated circuit-fabrication processes. The tall metal transmission lines will enable the development of high-power monolithic circuits as well as couplers and filters that require very high coupling. Using conductor thickness as a new variable in filter design permits the fabrication of elements requiring a wider than usual range of even- and odd-mode characteristic impedances by lowering the attainable odd-mode impedance without greatly influencing even-mode impedance. Bandpass and low-pass filters fabricated using 200-μm-tall nickel microstrip lines are demonstrated at X-band. Insertion losses of the network testing setup and waveguides were calibrated out using the thru-reflection-line (TRL) calibration method via LIGA-fabricated calibration standards. The high-aspect ratio and slope that the LIGA process offers will enable the design of end-coupled narrow-band bandpass filters and planar side-coupled 3-dB couplers. Filter structures were fabricated possessing coupling gaps with aspect ratios of better than 6.75 and conductor sidewall slope >89.9°, figures that are easily obtainable with the LIGA process. Additionally, W-band 3-dB coplanar waveguide-coupler LIGA geometries suitable for implementation on gallium arsenide or membrane (i.e., air dielectric) substrates are presented. A thin-film-to-LIGA tapered waveguide transition is presented which will allow integration of conventional planar transmission lines with these LIGA devices.**

***Index Terms*— Couplers, filters, micromachined transmission lines, power dividers.**

I. Introduction

THIS paper introduces new planar millimeter-wave and microwave transmission lines and filters micromachined using a variation of the LIGA (a German acronym with an English translation of lithography, electroforming, and molding) fabrication process (see Fig. 1). In the LIGA process, tall (10 μm–1 mm) metal structures with steep sidewalls are precision-formed on an arbitrary substrate material using deep X-ray lithography and plated metal [1], [2] (see Fig. 2). These structures are then used as a mandrel in subsequent injection molding. The LIGA variation presented in this paper utilizes the intermediate metal structures as the final device product in applications requiring high-precision conductors. LIGA-micromachined transmission lines will enable several important advancements in microwave and millimeter-wave integrated circuits. The tall metal transmission lines, when bounded by a good thermal conductor, are perfect for high-power applications due to the increased conduction interface which allows development of high-power monolithic circuits for commercial transmitter applications. The high-aspect conductor sidewalls possessing nearly vertical slope are ideal for devices which require very high coupling levels that are impossible to attain with conventional integrated transmission lines.

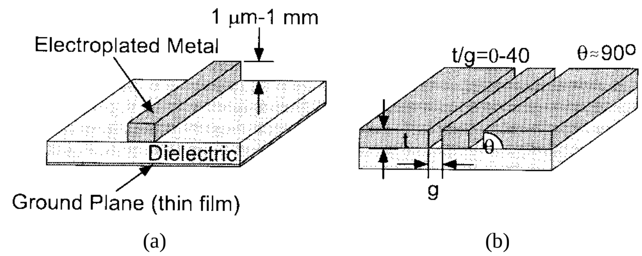

Fig. 1. LIGA planar transmission-line geometry for (a) microstrip line and (b) coplanar waveguide transmission line.

To exemplify the fabrication capabilities of LIGA, X-band microstrip stepped-impedance low-pass and broad-band bandpass filters were designed, fabricated using LIGA, modeled, and measured for their filter responses. Additionally, 270-μm-tall metal conductors were fabricated that possess high-aspect ratios and very steep sidewalls, two requirements for 3-dB single-section coupler manufacture. Quasi-static finite-difference (FD) analysis was used to determine W-band 3-dB coplanar coupler geometries suitable for application to gallium arsenide or membrane-based (i.e., air dielectric) substrates. These structures may be easily fabricated using the process demonstrated in this paper. To enable direct integration of LIGA filters and couplers with thin-film circuitry, a matched LIGA-to-thin-film planar waveguide transition is proposed. In addition to these specific applications, LIGA will allow the development of several new integrated coupler and filter circuits [3], [4] as well as new interdigital capacitors [4]. It is further possible to create a wide variety of three-dimensional (3-D) circuits with multiple X-ray exposure steps.

II. Theory and Design

An FD analysis [5] of LIGA microstrip lines on 420-μm-thick fused quartz ($\varepsilon_r = 3.81$ at 30 GHz) shows that a wide range of characteristic impedances are available for use in integrated micromachined circuits (see Fig. 3). The line

Manuscript received May 28, 1996; revised June 20, 1997. This work was supported by the University of Wisconsin-Madison Center for X-Ray Lithography.

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Publisher Item Identifier S 0018-9480(97)07102-0.

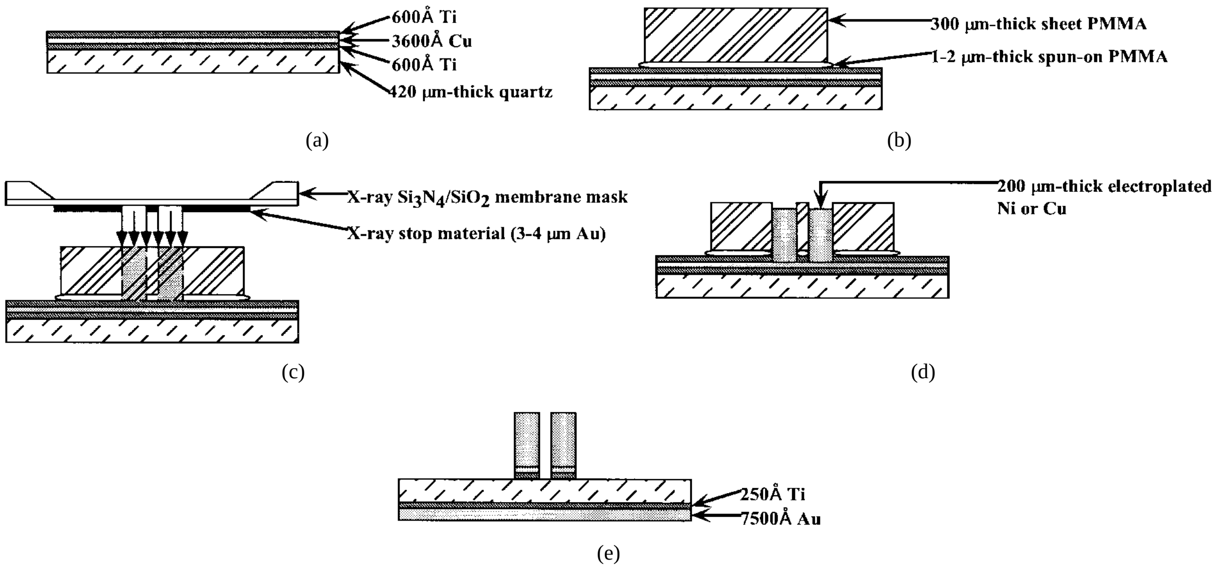


Fig. 2. Cross sections of the LIGA fabrication process. (a) Application of a plating base, (b) application of sheet resist, (c) X-ray exposure of resist, (d) conductor electroplating, and (e) final structure.

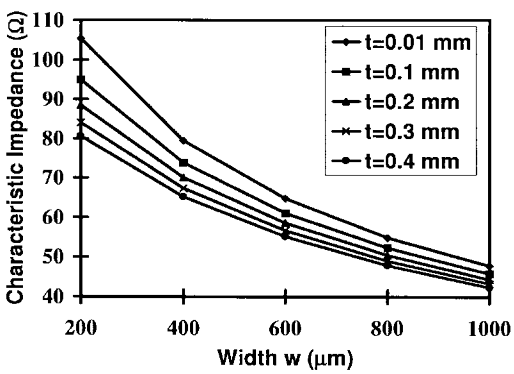


Fig. 3. Characteristic impedance data for the LIGA microstrip line generated using the FD method.

impedance decreases with increasing width, but decreases only slightly with increased thickness.

Due to the potentially high capacitance between tall closely-spaced adjacent lines, LIGA-fabricated lines are ideal for couplers and filters. The high-aspect ratio vertical-sidewall-structure fabrication capabilities of LIGA allow for flexible odd- and even-mode impedance specification in coupled-line planar circuits. The even-mode impedance is relatively invariant to conductor gap spacing (s) (see Fig. 4) when the spacing is small compared to total transmission linewidth while the odd-mode impedance, dominated by the line-to-line parallel-plate capacitance, is dominated by conductor spacing (s) and thickness (t).

The implication of a degree of freedom in selecting the line thickness in highly coupled LIGA structures is nearly independent control of even- and odd-mode characteristic impedances. The large degree of mode impedance control allows independent selection of a desired coupling coefficient and characteristic impedance. In addition to microstrip filter circuits, coplanar-waveguide-based filters and couplers can realize similar advantages from the LIGA fabrication process.

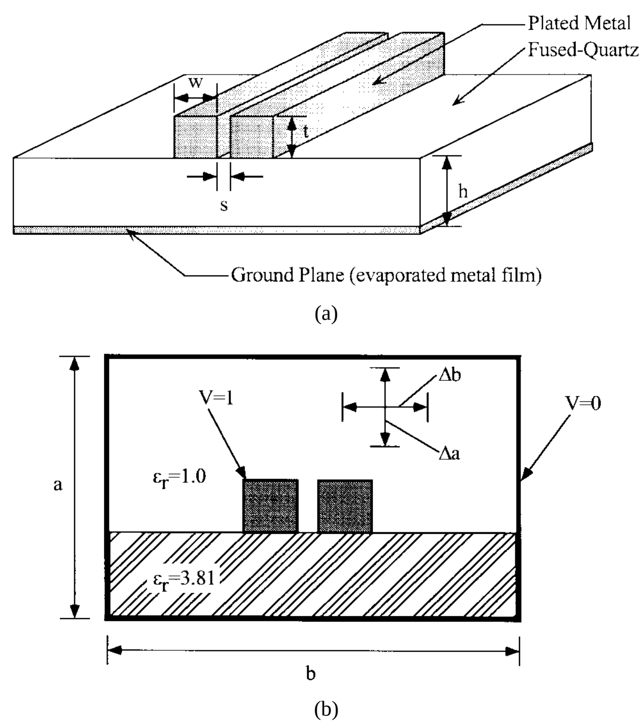


Fig. 4. LIGA geometry of a microstrip coupled-line section. (a) Definitions of dimensions and (b) geometry used in FD analysis.

A quasi-static FD analysis [5] of a vertical sidewall microstrip coupled-line structure was performed. Fig. 4(a) illustrates the coupled-line geometry used in the analysis with important dimensions. A closed boundary-value problem was formed by enclosing the microstrip cross section in a zero potential box [Fig. 4(b)] with typical a and b dimensions five to ten times the total filter height and width, respectively. Δa and Δb, the spatial voltage mesh dimensions, are typically $\Delta a = \Delta b =$ 5–10 μm. Fig. 5 presents the results of the FD analysis for conductor widths of 200 and 400 μm with

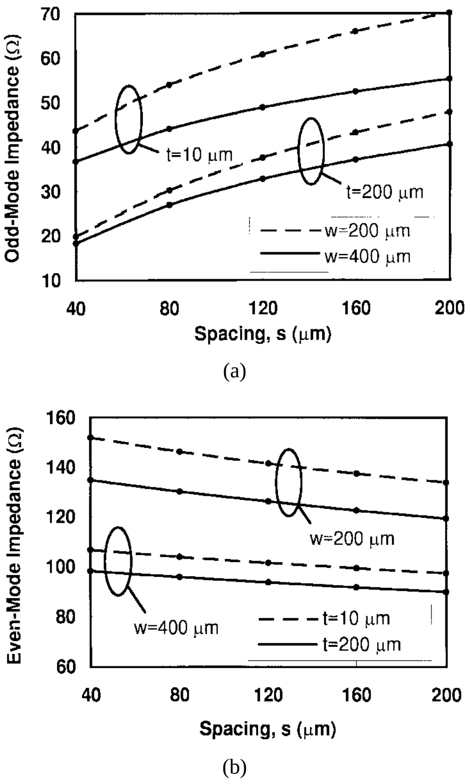
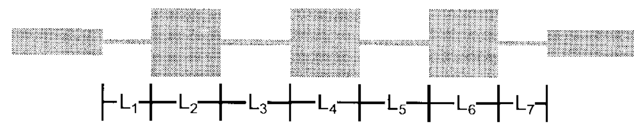


Fig. 5. Mode-impedance data for LIGA microstrip coupled-line sections. (a) Odd-mode characteristic impedance and (b) even-mode characteristic impedance.

Section	Width	Z_0
1 and 7	100 μm	106 Ω
2 and 6	1.5 mm	35 Ω
3 and 5	100 μm	106 Ω
4	1.5 mm	35 Ω



10 GHz Design	14 GHz Design
L_1=L_7=2.52 mm	L_1=L_7=1.8 mm
L_2=L_6=2.7 mm	L_2=L_6=1.929 mm
L_3=L_5=3.825 mm	L_3=L_5= 2.732 mm
L_4=2.885 mm	L_4=2.061 mm

Fig. 6. Seven-section stepped-impedance low-pass filter dimensions for 10- and 14-GHz designs.

conductor-to-conductor separation ranging from 40 to 200 μm. For impedance purposes, the 10-μm-thick conductor case represents a standard thin metal line, while the other cases represent LIGA geometries. Fig. 5(a) demonstrates the near independence of the even-mode characteristic impedance on coupled-line separation for a given conductor thickness. The even-mode impedance exhibits the expected dependence on total transmission linewidth ($s + 2w$). Fig. 5(b) illustrates the strong odd-mode impedance dependency on coupled-line thickness for a given separation. Note that the odd-mode impedance shows only a weak dependence on total coupled linewidth.

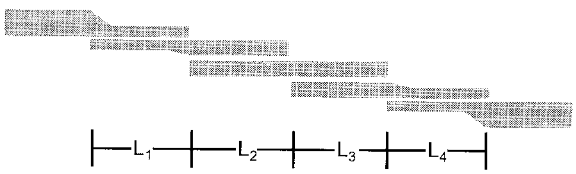
Performing multiple X-ray exposures during the fabrication process will allow different metal thicknesses within the same circuit, thereby permitting adjustment of characteristic impedances on a device-by-device basis. A fused-quartz substrate with low permittivity ($\varepsilon_r = 3.81$) is used for preliminary devices in order to minimize the difference between the even- and odd-mode phase velocities.

The minimum analyzed coupled-line separation of 40 μm is an order above the resolution limits for this fabrication process. The limitation on element-to-element spacing is set by the maximum feature aspect ratio, often defined as feature height-to-width ratio, achievable with the X-ray resist system. Aspect ratios on the order of 100 have been measured [1]. For comparison, thin-film structures fabricated with UV resist templates, and subsequently electroplated, usually possess aspect ratios below two. LIGA device sidewall slope does not limit coupling spacing since it is typically >89.9°. With this aspect ratio, 200-μm-tall conductors could be placed within 5-μm of each other. This capability is beyond the design requirements of most coupled-line filters since it results in extremely low odd-mode impedances (<5 Ω). Resolution patterns of 15-μm-wide alternating gaps and nickel structures are easily achievable with our current fabrication process for 200-μm-tall conductors. Maximum pattern resolution scales linearly with conductor height and, therefore, 7.5-μm gaps are possible if the conductor height is reduced to 100 μm.

Low-pass and wide-band bandpass LIGA microstrip filters with design frequencies of 10 and 14 GHz were fabricated and tested to demonstrate the potential of this novel coupled-line fabrication method. A stepped impedance low-pass filter with 200-μm-thick conductors was designed to have a 0.5-dB Chebyshev response (see Fig. 6). The 10-GHz version of this low-pass filter has a theoretical 3-dB cutoff frequency of 9.6-GHz and 20-dB attenuation at 12.2 GHz while the 14-GHz version was designed for a 3-dB cutoff frequency of 13.4-GHz and 20-dB attenuation at 17.1 GHz [6].

A coupled-line Butterworth bandpass filter was also designed for the 200-μm-thick conductor geometry (see Fig. 7). Quarter-wavelength parallel-line sections with two open-circuit ports were used as coupling elements. To enhance the manufacturing yield during the process development phase, a minimum coupled-line gap spacing of 200 μm was enforced on the design, corresponding to a 1:1 aspect ratio. In general, as the number of coupling sections in a bandpass filter is increased, the maximum required odd-mode coupling capacitance increases, in turn calling for tighter coupling gaps. Therefore, the aspect ratio of the coupling gap (s) is the practical limitation of bandpass-filter performance for both LIGA and conventional thin-film circuits. This performance limitation amplifies the advantage of LIGA fabrication over thin-film fabrication of coupled-line filters. Not only must the advantage of aspect-ratio gain be taken into account when comparing fabrication methods, but also feature profile definition accuracy. Thin-film metal profiles are difficult to

Section	Width	Gap	Z_{0e}	Z_{0o}
1 and 4	200 μm	200 μm	123 Ω	43 Ω
2 and 3	400 μm	400 μm	90 Ω	41 Ω



10 GHz Design	14 GHz Design
L_1=L_4=5.063 mm	L_1=L_4=3.616 mm
L_2=L_3=4.845 mm	L_2=L_3=3.461 mm

Fig. 7. Four-section wide-band bandpass filter dimensions for 10- and 14-GHz design.

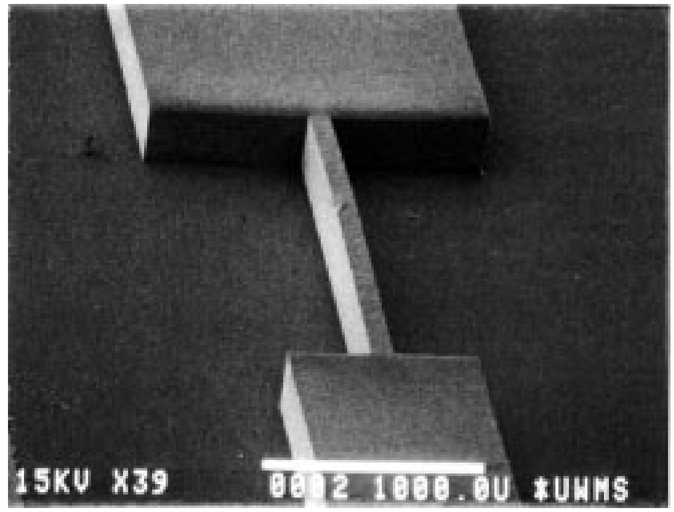
estimate *a priori* and may lead to large coupling errors for aspect ratios near or above unity. LIGA-fabricated sidewalls are of a well-defined predictable geometry which allows accurate 3-D numerical modeling (e.g., FD method). As a result of the characteristics of LIGA-fabricated coupled-line geometries, new filters with unprecedented minimal insertion-loss transition bandwidths, and in turn greater fractional bandwidths, are possible.

The bandpass filter designs were implemented with four coupling elements for a fractional bandwidth of 40% of the design frequency [6]. The 10-GHz version has 20-dB attenuation at 6.5 and 14.0 GHz, while the 14-GHz filter has 20-dB attenuation at 9.1 and 18.7 GHz.

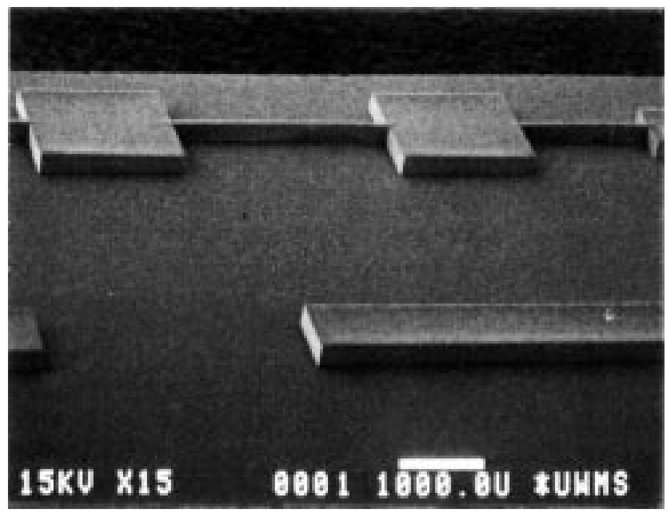
The narrow-band bandpass filter was designed for similar center frequencies and fabricated to demonstrate the coupling geometry capability of the LIGA process. A set of calibration standards were fabricated concurrently with the filter circuits to allow thru-reflection-line (TRL) calibration to null-out frequency-dependent insertion loss of the test fixture and filter substrate. For these first designs, length corrections to offset the edge capacitance of the lines due to the thickness of the conductors have not been attempted. Therefore, the actual response of the filters is expected to be shifted downward in frequency.

III. Fabrication

The LIGA fabrication process (see Fig. 2) utilizes coherent synchrotron X-ray radiation and a poly(methyl methacrylate) (PMMA) resist system with thickness ranging from 1 μm to 1 mm. In LIGA, a multilayer metal thin film is applied to a substrate to form a metal seed layer for subsequent electroplating. A high molecular weight PMMA resist is spun-on, cured, and monomer-welded to PMMA sheet resist [7]. The resist is exposed and immersion developed. Metal is then electroplated onto the metal film within the resist recesses and the resist is removed. The metal film is finally etched away to electrically isolate the plated structures.



(a)

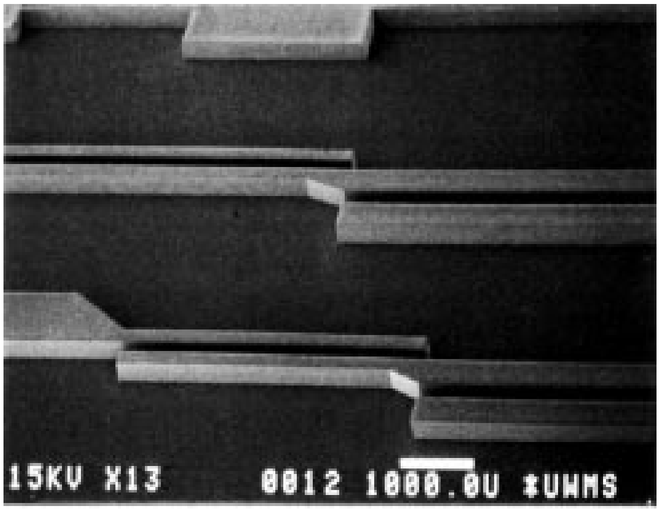


(b)

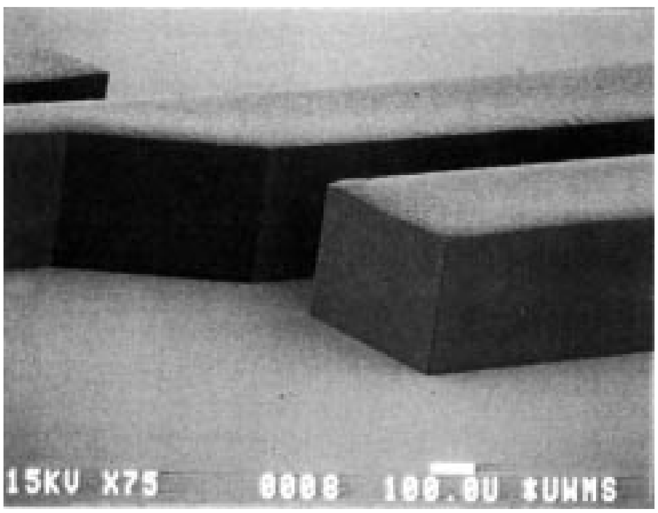
Fig. 8. SEM micrograph of LIGA stepped-impedance low-pass filter. (a) Perspective of an inductive section of the filter and (b) wide-angle view of filter with part of TRL calibration standard in foreground.

The goal of this process was the fabrication of 200-μm-thick LIGA microstrip filters on 420-μm-thick 3-in double-sided polished fused-quartz. A tri-layer metal film of titanium, copper, and titanium is sputter-deposited to a thickness of 600 Å/3600 Å/600 Å. The titanium layers provide an adhesive layer and stress buffer for the quartz and PMMA interfaces. After development of the PMMA, the titanium capping layer is etched and nickel electroplating (nickel sulfamate) is performed on the exposed copper following an activation step. Nickel was chosen as the strip conductor metal for the first fabrication runs, although gold or copper may also be plated. Finally, the PMMA is dissolved and the tri-layer metal thin film is etched away.

Optical and SEM characterization of the devices revealed structural heights with better than 1% thickness variation and 10% average height variance within the batch yield [see Figs. 8(a)–9(b)]. The height variance will likely improve for structures with less thickness since the thickness error depends



(a)



(b)

Fig. 9. SEM micrograph of LIGA coupled-line bandpass filter. (a) Perspective of filter constructed of nickel-plated conductor on fused-quartz and (b) close-up of coupling gap and sidewalls.

on the quality of plating rate calibration, which is easier to characterize for shorter plating times. The sidewall surface roughness resembles the roughness of the resist template sidewall (achieving <0.1-μm roughness), while the top nickel surface finish, like most thick plated deposits, is rougher ($\sim$1–2-μm roughness). Sidewall slope is greater than 200:1.

IV. Filter Measurements

220-μm-tall filters were measured using an HP 8722C network analyzer with a custom microstrip test fixture. Short-open-load-thru (SOLT) calibration was performed using coaxial HP calibration standards as well as TRL calibration via integrated calibration standards. TRL provided better wide-band calibration due to its ability to calibrate-out the test fixture-to-substrate insertion losses over a 3–24-GHz span.

Transmission characteristics of the 10-GHz tandem low-pass filter are plotted with $|s_{21}|$ transmission data generated

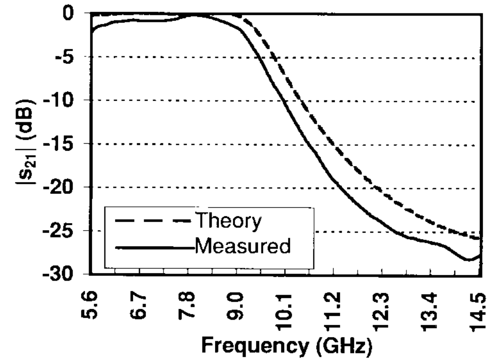


Fig. 10. Filter response of 10-GHz LIGA stepped-impedance low-pass filter. The solid line is the measured response and the dashed line is the theoretical response curve.

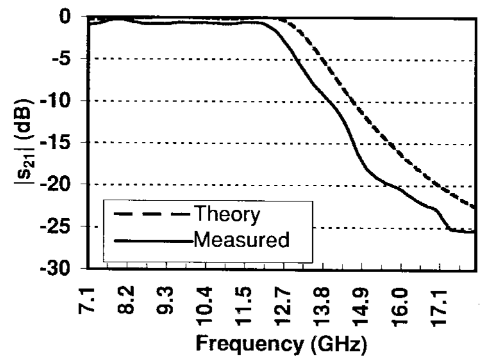


Fig. 11. Filter response of 14-GHz LIGA stepped-impedance low-pass filter. The solid line is the measure response and the dashed line is the theoretical response curve.

by a subnetwork calculation-based circuit-analysis program[1] in Fig. 10. The filter was designed for a transition band of 3–20 dB attenuation extending from 10 to 14 GHz. The measured response curve is shifted downward in frequency by 0.3 to 1.2 GHz (i.e., compressed). The filter was designed to produce a Butterworth response and remains reasonably flat from 5.8 GHz to its corner frequency, ranging between -1.2 dB and a minimum insertion loss value of -0.13 dB at 7.9 GHz. The measured filter response is -3 dB at 9.22 GHz and reaches -20 dB at 11.4 GHz, giving the transition band a width of 2.18 GHz, which exceeds the requirements of the design.

The 14-GHz low-pass filter was designed for a -3- to -20-dB transmission transition band from 14 to 20 GHz. Like the 10-GHz filter, its response curve is shifted downward in frequency with a filter response of -3 dB at 12.7 GHz and -20 dB at 15.8 GHz (see Fig. 11). Minimum insertion loss is -0.15 dB at 8.07 GHz. The filter has a flat response from 7.1 GHz up to its corner frequency. Both of the measured low-pass filter responses matched the theoretical response curves to within 5.4% at the -3-dB corner frequency while exhibiting attenuation similar to the theoretical responses above the corner frequency.

The 10-GHz four-section coupled-line bandpass filter has a measured center frequency of 9.7 GHz, exhibiting the same

[1] PUFF Version 2.0, "Computer aided design for microwave integrated circuits," R. Compton and D. Rutledge, Cornell University, Ithaca, NY, 1991.

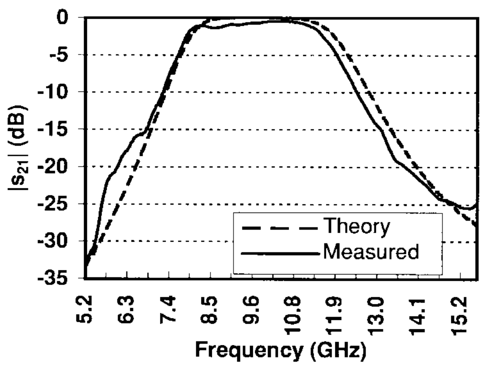


Fig. 12. Filter response of the 10-GHz LIGA coupled-line bandpass filter. The solid line is the measure response and the dashed line is the theoretical response curve.

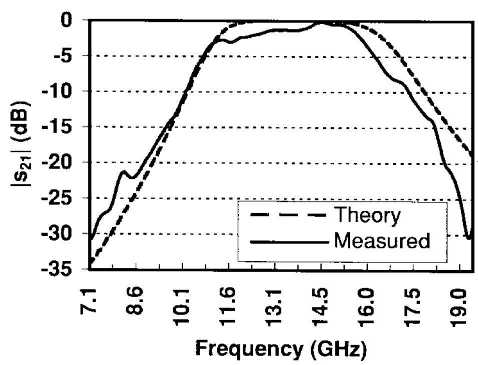


Fig. 13. Filter response of the 14-GHz LIGA coupled-line bandpass filter. The solid line is the measure response and the dashed line is the theoretical response curve.

frequency shifting (~0.2 GHz) phenomena as seen with the low-pass filters (see Fig. 12). The measured response curve matches the theoretical curve's −3-dB transition points to within 2.5%. The minimum insertion loss is −0.45 dB at 10.12 GHz. The attenuation rate is nearly identical for the measured response and the theoretical response from the passband down to −15 dB, with some deviation thereafter. The wide-band characteristics of this filter design are demonstrated by the measured 38% fractional bandwidth.

The 14-GHz bandpass filter response is less symmetric than the response of the 10-GHz filter, but did achieve a minimum insertion loss of −0.15 dB at 14.6 GHz (see Fig. 13). The filter response is shifted downward slightly more than the 10-GHz filter response (~0.3 GHz). The measured response's 3-dB corner frequencies match the theoretical response to within 4.4%. The measured response achieves 30-dB attenuation at 7.2 and 19.3 GHz. The measured fractional bandwidth is approximately 34%.

A simple equivalent circuit model of a −90° phase shifter between two transmission-line sections of equal electrical length and characteristic impedance was used to design the coupled-line bandpass filters. It is known that for large deviations from the designated center frequency, this model becomes rapidly inaccurate. Elliot reports 10.5% normalized input impedance error between the coupling section impedance and this simple equivalent-circuit model for a 20% fractional bandwidth [8]. The wide-band responses presented do not seem to affirm Elliot's findings, although small disagreements between measured response and theory do exist. Future wide-band filter design will follow work by Matthei which has accurately modeled 2:1 bandwidths using more complex reactance transformations [9]. Other filter-response performance enhancement will concentrate on compensating for the open-end effects of the low-impedance transmission-line sections, a change of conductor metal from nickel to copper, and improving the RF performance of the test fixture.

It is important to note that although a designer can model filters with extremely large bandwidths, it is extremely difficult to fabricate thin-film filters with fractional bandwidths greater than 50% using coupled-line filter geometries because of the UV photolithographic aspect-ratio limitations presented in Section II. Many designers implement filters with fractional bandwidths >20% using commensurate-line filters [8]. For comparison, a commensurate-line filter version of the 14-GHz bandpass filter presented in this paper would require the fabrication of a transmission line loaded by an array of microstrip stubs (2.5–5 mm each in length) placed in parallel and series with the main line. Such requirements lead to less spatially efficiency and more fabrication complexity than that which the LIGA bandpass filters presented offer.

V. Further Applications of LIGA Technology

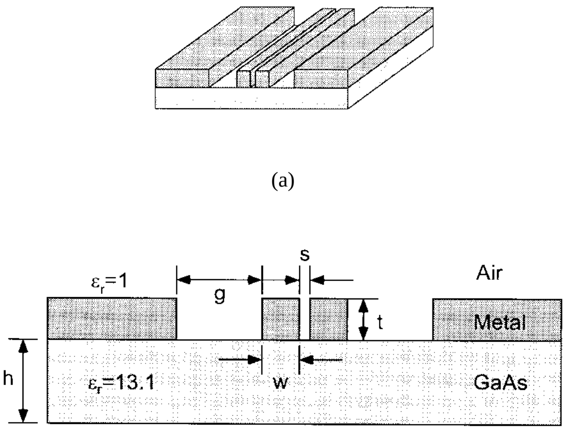
As stated previously, one major application area of the LIGA planar-circuit technology is the development of novel millimeter-wave filters and couplers that cannot be fabricated using conventional fabrication technology. One specific example is single-section 3-dB couplers for gallium–arsenide (GaAs) substrates and air (i.e., thin membrane-supported) substrate applications. A 3-dB coupler with an input impedance of 50 Ω requires even- and odd-mode impedances of 120 and 20 Ω, respectively [6]. The low odd-mode characteristic impedance is impossible to practically achieve using planar transmission lines because of limitations on interconductor capacitance and control of this capacitance using thin-film or conventional electroplating processes, as presented in Sections II and III.

Recently, one group increased the odd-mode capacitance by fabricating planar lines on top of each other with polyimide in between [10]. While the group was able to fabricate 3-dB coplanar waveguide couplers for the K- and Ka-bands, their design requires a five-level fabrication process, and a majority of the coupled fields are concentrated in the lossy polyimide region. Another group has recently introduced 3-D u-shaped microwire technology which delivers ultra-compact transmission-line geometries [11]. Although layout efficient, this technology utilizes lossy polyimide isolation layers and is limited to structural heights in the tens of microns. These two fabrication properties imply greater limitations than LIGA offers with regard to phase velocity adjustment and loss reduction.

Quasi-static FD modeling indicates that W-band 3-dB couplers suitable for 94-GHz operation may be LIGA fabricated on gallium arsenide ($\varepsilon_r = 13.1$) using a single 5.8-μm-thick

TABLE I
W-BAND (94-GHz) GEOMETRY

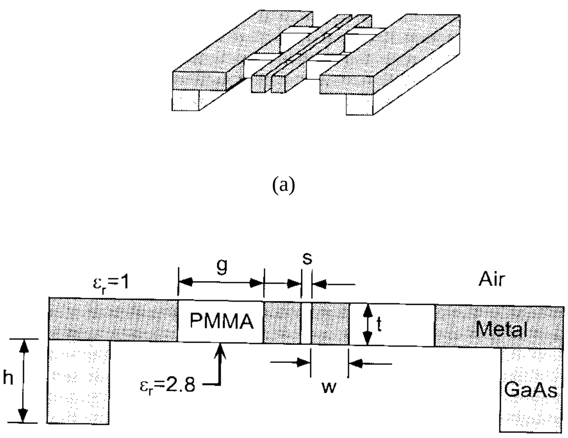
Dimension	Value
Separation (s)	1.7 μm
Thickness (t)	5.8 μm
Ground gap (g)	37.5 μm
Subst. height (h)	>120 μm
Width (w)	5.8 μm



(a)

(b)

Fig. 14. GaAs 3-dB coupled-line coupler. (a) LIGA perspective and (b) dimensional definitions. Table I lists FDM-computed W-band dimensions.



(a)

(b)

Fig. 15. Air bridge 3-dB coupled-line coupler. (a) LIGA structure with polymer support links and (b) dimensional definitions. Table II lists FD method computed W-band dimensions.

LIGA level and the geometry specified in Fig. 14 and Table I. This LIGA coupled-line 3-dB coupler would require a gap aspect-ratio of 3.41 and a minimum gap spacing of 1.7 μm, both of which are easily achieved using our present LIGA process.

An air-substrate CPW 3–dB coupler geometry that benefits from equal even- and odd-mode phase velocities may be fabricated using a one-level LIGA process and selective removal of portions of an underlying gallium arsenide substrate via bulk micromachining. A silicon nitride membrane or polymer support links [Fig. 15(a)] may be used to suspend the filter

TABLE II
W-BAND (94-GHz) GEOMETRY

Dimension	Value
Separation (s)	17.3 μm
Thickness (t)	86 μm
Ground gap (g)	65 μm
Subst. height (h)	>200 μm
Width (w)	86 μm

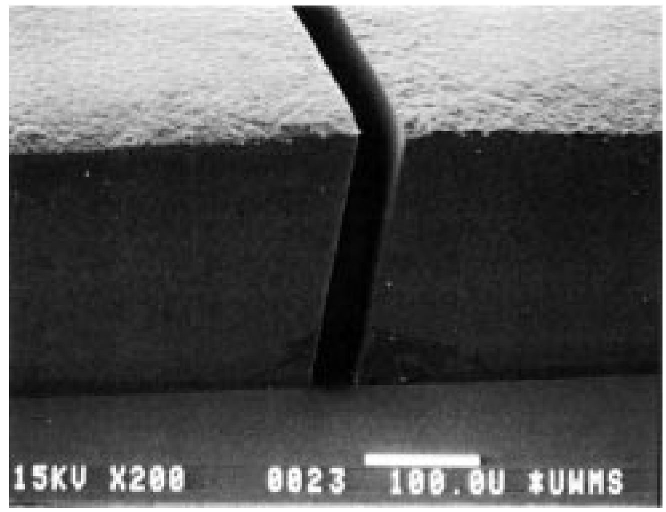


Fig. 16. SEM micrograph demonstrating LIGA's potential to permit fabrication of extreme coupling geometries.

transmission lines. A suitable geometry was developed using the FD method and is presented in Fig. 15(b) and Table II. The geometry, as presented in Table II, is suitable for operation in the W-band. An air-based W-band coplanar waveguide (CPW) coupler would require 86.3-μm-thick metal with a minimum gap spacing of 17.3 μm, corresponding to an aspect ratio of 5 which is easily attainable with a one-level LIGA process. In both the GaAs and air-based structures, the 3-dB couplers benefit from the reduced material losses and lower complexity that LIGA offers. High-aspect coupling gap work has been demonstrated on tandem narrow-band microstrip filter geometries [see Fig. 16]. The narrow-band filters shown are ~270 μm in height with a uniform coupling gap of 40 μm, providing an aspect-ratio of 6.75.

While it will be trivial to align and integrate LIGA couplers with planar active circuits, efficient thin-film line-to-LIGA-line transitions must be developed before the LIGA circuits will see wide usage. One potential transition is illustrated in Fig. 17. In this simple transition, the LIGA section and the planar line are tapered opposite to each other such that a constant 50-Ω characteristic impedance is maintained over the entire length of the line.

VI. CONCLUSION

A new method for the fabrication of planar microwave and millimeter-wave passive devices has been presented. The LIGA fabrication process was used to fabricate 10 and 14 GHz low-pass and 40% fractional bandwidth bandpass filters on fused-quartz. TRL-calibrated measurements of the LIGA

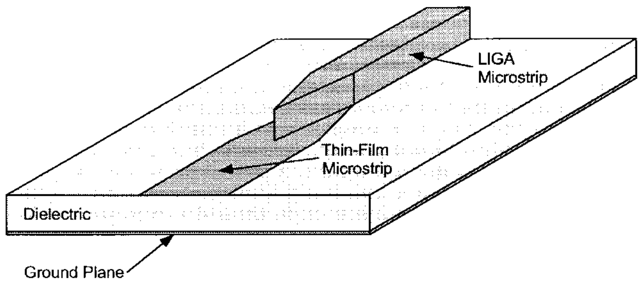


Fig. 17. Conceptual perspective drawing of a low-loss LIGA-to-thin-film microstrip transition structure.

coupled-line filters agreed well with theoretical data generated by a numerical package. The LIGA process has the ability to permit wide-band filter design previously thought intractable in integrated circuit applications.

The conductor thickness control that LIGA offers allows independent control of even- and odd-mode coupled-line impedances and specification of a coupling factor. Quasi-static FD analysis was used to design 50-Ω single-section 3-dB coplanar waveguide couplers on gallium arsenide and air substrates. The filter aspect ratios required to fabricate these 3-dB couplers is easily achieved with the current fabrication process, as was demonstrated with the fabrication of end-coupled narrow-band bandpass filter structures. With the development of matched LIGA-to-thin-film planar circuit transitions, LIGA has the potential to gain widespread use in passive-device applications requiring a high degree of coupling.

ACKNOWLEDGMENT

The authors are greatly indebted to Prof. F. Cerrina and G. Wells of the University of Wisconsin-Madison, for their assistance with the LIGA process. The authors also wish to thank Prof. L. Katehi and Prof. G. Rebeiz of the University of Michigan at Ann Arbor, for providing a means to test the initial filter circuits.

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