Demonstration of Integrated Solenoid Transformer Balun in Glass Substrate Utilizing TGVs

Jein Yu, Insup Han, and Jongmin Yook
Korea Electronics Technology Institute
Seongnam, Korea
Ph: +82-31-789-7227
Email: jein.yu@keti.re.kr

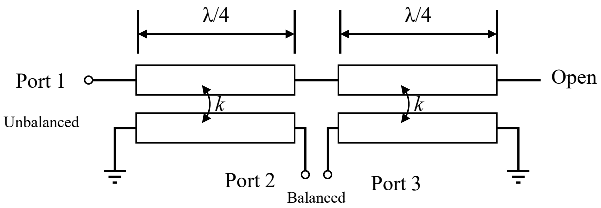
Abstract
This paper presents the implementation of a solenoid transformer balun within a glass substrate using through-glass vias (TGVs). We designed a Marchand type balun, based on a 3D solenoid transformer and integrated into a glass substrate, using TGVs realized through the laser induced deep etching process. The fabricated balun features a compact footprint of 1.18 × 0.61 × 0.46 mm3, good magnitude and phase balance performance, and a wide frequency bandwidth. The measured results align well with the simulations, showing a fractional bandwidth of over 50%, a common mode rejection ratio (CMRR) above 23dB, and a low insertion loss of less than 1.15dB, reaching a minimum of 0.45dB.

Key words
RF Balun, Solenoid transformer, TGV, Glass substate, Integrated passive device

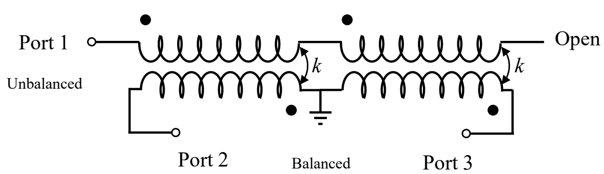
I. Introduction
As the "More than Moore's" paradigm continues to evolve, the complexity of advanced packaging is increasing, particularly with the rise of 2.5D packaging technology that employs interposer substrates, playing a key role in this technology area. Recently, due to the increasing size requirements for interposer substrates, glass interposer technology is gaining attention. Compared to silicon, glass enables panel-level processing, which offers a cost-effective solution, and it also aligns with silicon in terms of Coefficient of Thermal Expansion (CTE), along with having low RF loss characteristics. Consequently, it is remarkably well-suited as a substrate for advanced packaging applications [1]. The first important step in glass interposer fabrication is the creation of through-glass vias (TGVs). Over the past decade, various methods such as mechanical drilling, laser ablation, and etching using electrical discharge have been developed [2]. However, they often struggle to meet the requirements of advanced package interposers in terms of minimum via size and aspect ratio. Vitrion has reported the ability to fabricate high aspect ratio TGVs smaller than 10μm using laser induced deep etching technology [3]. This technique utilizes a laser to induce local phase changes in the glass. By locally irradiating the glass substrate with a laser, phase changes are induced in specific regions of the glass. These phase-changed regions have a significantly higher etching rate compared to the unaffected areas. This enables the formation of high aspect ratio micro vias on the glass substrate.
The low RF loss of glass substrates makes them suitable for utilization as substrates for IPDs [4]. Specifically, by utilizing 3D MEMS process, it becomes possible to implement high-Q 3D inductors, which enables the integration of 3D IPDs within the substrate itself [5-7]. Spiral inductors can be embedded within the substrate [5], and the TGVs can be utilized to implement solenoid inductor structures [7]. Moreover, by using TGVs, 3D IPDs mounted on both sides can be employed to minimize the size of components [6].
In this paper, we present a solenoid transformer balun fabricated in a glass substrate using through-glass vias (TGVs). The TGVs were fabricated through a process of laser-induced chemical etching. To make a tightly coupled transformer, we designed a solenoid transformer that consist of two redistribution layers (RDLs) on each side of the glass substrate.

II. Design of the transformer balun
As a basic RF passive circuit, a balun converts balanced input to unbalanced output and vice versa, serving essential roles in the receiver of a dipole antenna or in the transition between

differential and single-ended signals. To obtain a compact footprint, good magnitude and phase balance performance, and wide frequency bandwidth, we opted for a Marchand balun architecture. Marchand baluns are constructed from two identical coupled line sections, which can be realized by various coupled line designs [8]. Implementing the coupled sections with transformers offers the advantage of small footprint while maintaining tight mutual coupling. In this study, we designed a Marchand type balun using a 3D solenoid transformer facilitated by through-glass vias (TGVs).



(a)



(b)

Fig. 1. (a) Marchand balun (b) Demonstrated solenoid transformer balun

Fig.1 (a) illustrates the conventional Marchand balun structure. As indicated in Fig.1 (b), each coupled section can be substituted with a transformer. By considering the physical characteristics of a solenoid transformer, transformers with opposing polarities can be used, which enables the relocation of the ground tap to the balun's center. This leads to a simplified and more compact circuit design. Nonetheless, since the transformer's wiring is implemented on a glass substrate using a planar process, a design with opposite polarity requires crossing wires, which implemented by 2 RDLs on each side of the substate.

We designed the proposed balun using a full 3D EM simulator, HFSS. With a center frequency of 3.5GHz, it was optimized to achieve a fractional bandwidth of more than 50%. Fig. 2 (a) presents a 3D model of the proposed balun. The glass substrate is 400 µm thick, and the diameter of the TGV is 30 µm and pitch of the TGV is 80 µm. Two layers of 15 µm thick copper winding were formed on each side of the glass substrate using 20 µm ABF (Ajinomoto Bonding Film). Fig. 2(c) and (d) show the primary and secondary solenoid windings of the balun, respectively. the primary solenoid consists of the top surface's metal 1 and the bottom surface's metal 2 layers. Conversely, the secondary solenoid uses metal 2 on the top surface and metal 1 on the bottom. Consequently, the two solenoids are nearly identical, and both the unbalanced input (at port 1) and the balanced ports (at port 2 and port 3) have the same impedance (1:1 transformer). The total length and width of the balun are 1180 µm and 610 µm, respectively.

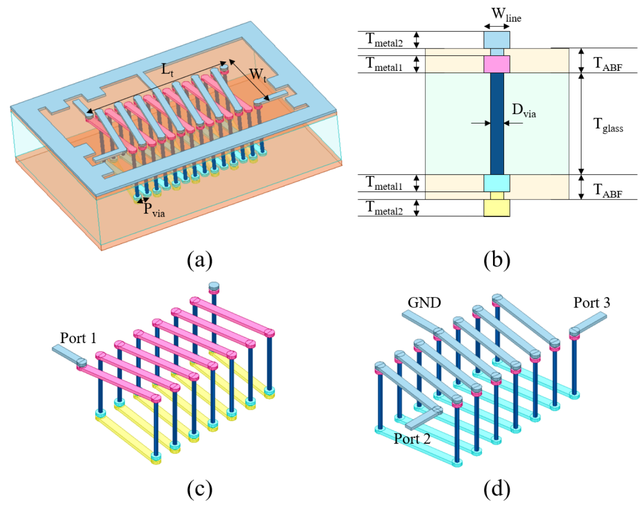


Fig. 2. Design of the proposed solenoid transformer balun (a) 3D model of the balun, (b) stack-up of the balun, (c) the primary solenoid winding, and (d) the secondary solenoid winding

Table 1. Design parameters of the proposed balun

$\mathbf{T_{glass}}$	400 µm	$\mathbf{D_{via}}$	30 µm
$\mathbf{T_{metal1}}$	15 µm	$\mathbf{P_{via}}$	80 µm
$\mathbf{T_{metal2}}$	15 µm	$\mathbf{W_{line}}$	55 µm
$\mathbf{T_{ABF}}$	20 µm	$\mathbf{W_t}$	610 µm
$\mathbf{L_t}$	1180 µm		

III. Fabrication and results

The fabrication process for the glass balun is shown in Figure 3. Initially, Through-Glass Vias (TGVs) were fabricated using the Laser Modification Chemical Etching (LMCE) process provided by Joongwoo M-tech (South Korea). The process utilizes LASER inducing a phase transition in the Boro-33 glass substrate, allowing for anisotropic etching of the glass substrate in a chemical etchant. Since the laser-modified portion is etched more rapidly compared to the untreated glass portion, it is possible to etch micro-vias and vertical cavities with very high aspect ratio. In this study, we could fabricate TGVs with 30µm diameter on the 400µm-thick glass wafer.

Following TGV fabrication, the first step in RDL formation involved the deposition of a seed layer on the glass substrate. Subsequently, Metal 1 layers on the TGV sidewalls, top, and bottom were formed using a semi-additive patterning process. To electrically insulate these layers, ABF GL-103 was vacuum-laminated onto both sides of the substrate. Next, via holes between Metal 1 and Metal 2 layers were formed using an ESI-5330 UV-YAG laser system. After laser drilling, the Metal 2 layers were fabricated on the top and bottom surfaces using the same semi-additive patterning process employed for the Metal 1 layers.

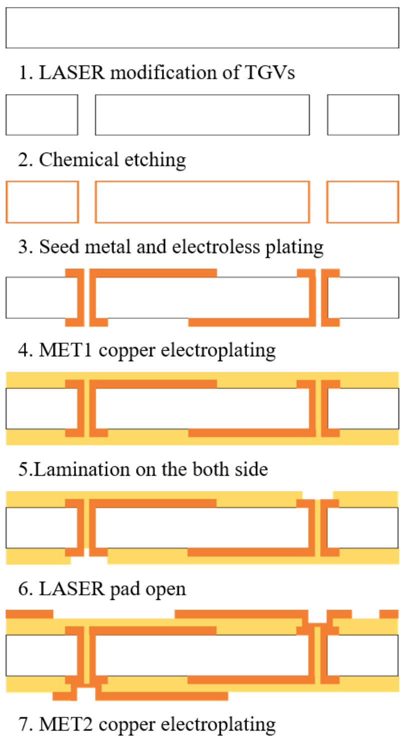


Fig. 3. Fabrication flow of the balun on glass substrate

Figure 4 presents various stages of the fabrication process. Figure 4(a) shows the TGVs on a glass substrate. The 15µm-thick cu electroplated TGVs and metal 1 layer on the glass substrate are shown in Figure 4(b). The top view of TGVs including ABF fill-up and laser-drilled vias is shown in Figure 4(c). Lastly, Figure 4(d) provides the final structure of the fabricated balun.

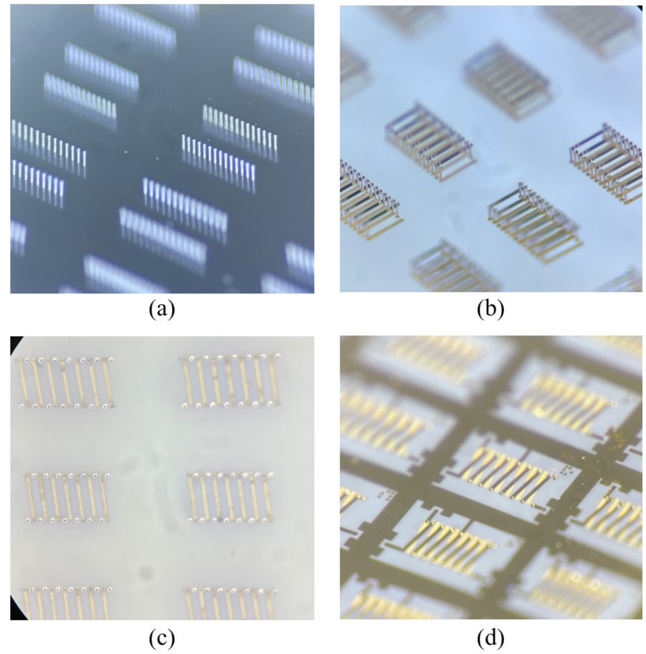


Fig. 4. Optical microscope photograph of (a) TGV etching, (b) VIA filling and Metal 1 Cu plating, (c) ABF LASER via opening, and (d) fabricated baluns.

The 3-port S-parameter results from both the simulation and measurement of the proposed balun are presented in Figure 5. These measurements were carried out using a vector network analyzer. Each port was evaluated at a 50-ohm impedance, then ports 2 and 3 were normalized to 25 ohms. The S-parameters from both the measurements and the simulation align well.

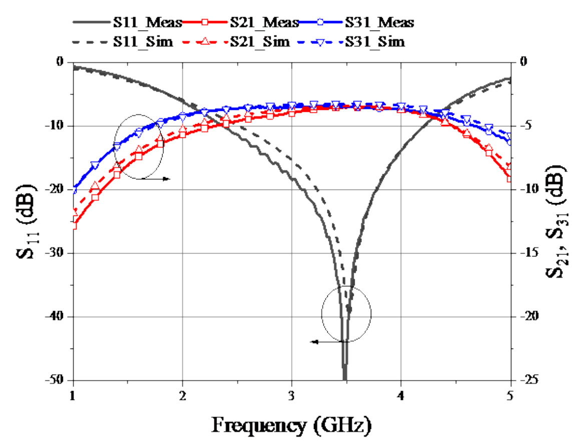


Fig.5. 3 Port S-parameter

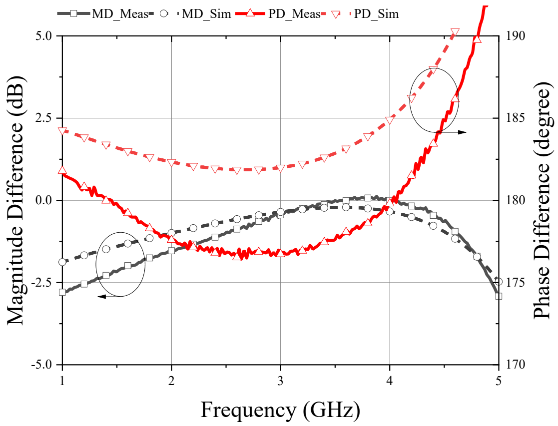


Fig.6. Magnitude and phase imbalance

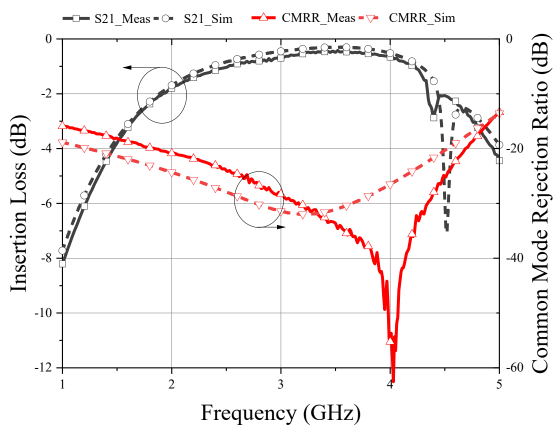


Fig.7. Insertion loss and common mode rejection ratio

The center frequency of the balun is 3.48GHz. And the bandwidth of -10 dB return loss is from 2.4GHz to 4.2GHz. This gives us a fractional bandwidth of 51%. Within the frequency bandwidth, the imbalance in magnitude and phase were found to be less than 1.1dB and 3.2°, respectively. The common mode rejection ratio (CMRR) measured as 33.58dB at 3.5GHz and remained above 23dB throughout the range of operational frequencies. The insertion loss was at most 1.15dB within the operational frequency bandwidth. The minimum IL at the center frequency of 3.48GHz is only 0.45dB. The fabricated size of the balun is 1.18 × 0.61 × 0.46 mm3.

IV. Conclusion

In this study, we have successfully implemented a Marchand type solenoid transformer balun within a glass substrate using the high aspect ratio TGV fabrication process. The balun we designed exhibits a compact size, superior magnitude and phase balance performance, as well as a broad frequency bandwidth. This research demonstrates the potential of glass substrates for the integration of high-performance IPDs and is expected to contribute to the field of advanced packaging.

Acknowledgment

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