K-band bandpass filter using fully micromachined substrate integrated waveguide platform with dual copper posts in glass dielectrics

Ik-Jae Hyeon and Chang-Wook Baek✉

A K-band bandpass filter (BPF) based on the fully micromachined substrate integrated waveguide (SIW) structure has been demonstrated. In the proposed SIW platform, borosilicate glass reflowed into the silicon trench is used as a dielectric substrate, and the vias are formed by filling the glass mould with electroplated copper after removing the embedded silicon part. The BPF's characteristics are realised by introducing dual inductive post structures into the SIW platform. The insertion loss and 3 dB bandwidth of the fabricated BPF were measured to be 2.46 dB at 29 GHz and 7.2%, respectively. The proposed BPF platform has high potential for low-loss, compact SIW-based millimetre-wave tunable filters owing to its mechanical robustness and integrity with MEMS tuning devices.

Introduction: In substrate integrated waveguides (SIWs), an electrical signal propagates in the TE mode of conventional three-dimensional rectangular waveguides with very small leakages. This allows the SIW to have a low-loss property and high-power capability, while maintaining its compact, planar structure. These characteristics of SIWs have been applied in miniaturisation technology for high-performance microwave and millimetre-wave circuits and systems for about 10 years. Recent researches have focused on tunable resonators and filters by using electrical tuning elements. Varactor-tuned resonators using a half-mode SIW loaded with complementary split ring resonators (CSRRs) were demonstrated at 2.9–3.4 GHz [1]. A tunable filter, by placing already packaged radio-frequency MEMS switches on via structures of the SIW, was also reported at 1.2–1.6 GHz [2]. These approaches, however, are not adequate for millimetre-wave applications due to the difficulty in the integration of tunable components with conventional PCB-based microwave substrates. We have demonstrated micromachined SIWs and CSRR-loaded SIW filters using a low-loss benzocyclobutene (BCB) polymer dielectric substrate and metal-coated silicon vias, bearing in mind the integration with MEMS tunable components for fully-integrated millimetre-wave platforms [3, 4]. However, the direct integration of MEMS components onto this SIW filter was not successful because of the processing difficulties arising from the deformation of the soft polymer substrate in the following high-temperature steps.

In this Letter, a fully micromachined SIW filter platform suitable for direct integration with MEMS tunable devices is designed and fabricated. Thermally reflowed borosilicate glass is used as a dielectric material, which provides superior mechanical hardness and immunity to the process temperature than soft BCB polymer. With this platform, dual inductive metallic posts utilising electroplated copper metal vias embedded in glass are used to demonstrate bandpass filter (BPF) responses at the K-band.

Structure and design: The schematic view of the proposed BPF structure based on the SIW is illustrated in Fig. 1. The BPF is composed of three parts: a dielectric substrate with metal vias, a top metal layer and a bottom metal layer. The dielectric substrate for the SIW is made from borosilicate glass refilled into the etched silicon trench by a thermal glass reflow process. Metal vias are embedded in this glass substrate by the electroplating of copper using the glass layer as an electroplating mould. Copper via arrays at the edges of the SIW substitute effectively for the sidewall of the waveguide. Microstrip lines, propagation mode transformers and an outer metal part of the SIW are formed on top of the substrate. The signal is excited on the 50 Ω microstrip lines, and the tapered line transformer is used for impedance matching between the microstrip lines and the SIW as well as for changing the propagation from TEM mode to TE mode. At the bottom of the substrate, a sputtered gold layer is formed as a ground plane of the SIW.

Dual inductive copper posts are formed inside of the SIW to realise BPF characteristics. Metallic post structures are adopted because they can be simply implemented in the SIW along with the sidewall via arrays at the same time during the fabrication process flow. In terms of filter design, the shunt metallic inductive post structure can be modelled as an equivalent circuit of π-network [5], and then be transformed into a K-inverter [6]. By using this model, the bandpass characteristics can be obtained using the filter synthesis technique for inductive posts in rectangular waveguides as described in [6]. In addition, these metallic post structures might be used as DC driving electrodes of MEMS actuators without complex bias schemes for tunable filters, by the proper modification of top metal patterns and the integration of MEMS tunable capacitors or switches directly onto these posts.

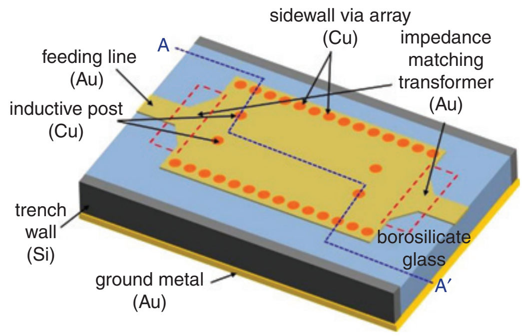

Fig. 1 *Schematic view of proposed micromachined SIW-based BPF*

The design of the narrowband BPF prototype was performed using a commercial electromagnetic simulator, where the dielectric constant and loss tangent of the borosilicate glass were set to be 4.6 and 0.0037, respectively. The dimensions of the top metal layer and vias are shown in Fig. 2, and the thickness of the SIW substrate is designed to be 350 µm. The simulated centre frequency is 29.1 GHz and the 3 dB bandwidth is calculated to be 4.2%. The simulated insertion loss is 2.65 dB at the resonant frequency.

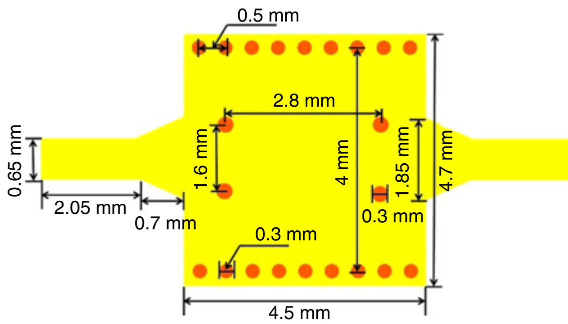

Fig. 2 *Top view of designed SIW BPF layout*

Fabrication process: The fabrication process of the BPF is illustrated in Fig. 3, where formation of copper vias in reflowed glass is adopted from the previous researches [7, 8]. Silicon trenches and pillars with a depth of 370 µm are formed in a 4-inch, 500 µm-thick (100) p-type silicon wafer ($\rho = 0.01$–0.02 Ω·cm) through silicon deep reactive ion etching (DRIE). A 4-inch borosilicate glass wafer is anodically bonded to the etched surface under a vacuum environment. The wafer stack is heated up to 800°C in a tube furnace and kept for 8 h. During this procedure, the melted glass reflows into the trench around the silicon pillars due to the low pressure in the sealed trench. Reflowed glass over the silicon trench is lapped and polished until silicon pillars embedded in the glass are exposed. Then, second DRIE process is performed to selectively remove the silicon pillars in a glass. The empty holes in the glass are filled with copper to form metal vias and posts by an electroplating process using low-resistivity silicon as a seed layer. After polishing the overplated copper down to the glass surface, a chrome (10 nm)/gold(500 nm) layer is deposited as a ground metal layer. Silicon, glass and copper vias at the opposite side of the substrate are lapped and polished down together to control the total thickness of the SIW to be 350 µm as designed. The ground metal layer helps to prevent the metal vias and posts from being pulled off from the glass during this step. Finally, a 3 µm-thick gold layer is electroplated to form the top metal layer. The photograph of the fabricated SIW filter is shown in Fig. 4. The remaining unnecessary boundary silicon part is removed away during the dicing of the sample, and the total device size is 10×4.8 mm^2.

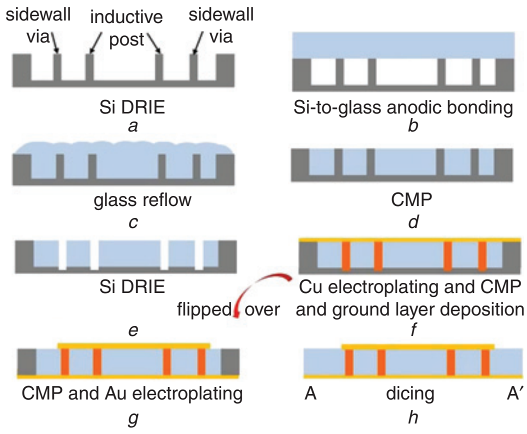

Fig. 3 *Fabrication process of BPF*

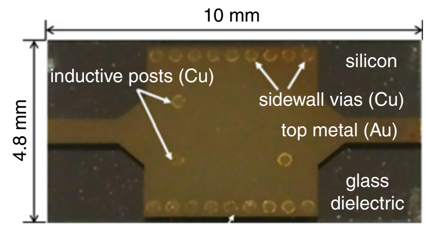

Fig. 4 *Photograph of fabricated BPF*

Experimental results: Performances of the fabricated BPF were measured by a HP 8510C vector network analyser using a commercial universal test fixture (3680 V, Anritsu Corp.) for interfacing. A standard SOLT calibration was used with a commercial calibration kit (36804B-10M, Anritsu Corp.). The measured *S*-parameters were compared with the simulation results, as shown in Fig. 5. The measurement results are in close agreement with the simulated predictions. The insertion loss was measured to be 2.46 dB at 29 GHz and the 3 dB bandwidth of the fabricated BPF were calculated to be 7.2%. The measured return loss was better than 15 dB at the resonant frequency. The measured insertion loss value is comparable with our previous results of SIW filters at the Ku-band loaded by CSRRs [4], where lower-loss BCB polymer (loss tangent of 0.0008 at 10 GHz) is used as a dielectric substrate material instead of borosilicate glass as in this Letter.

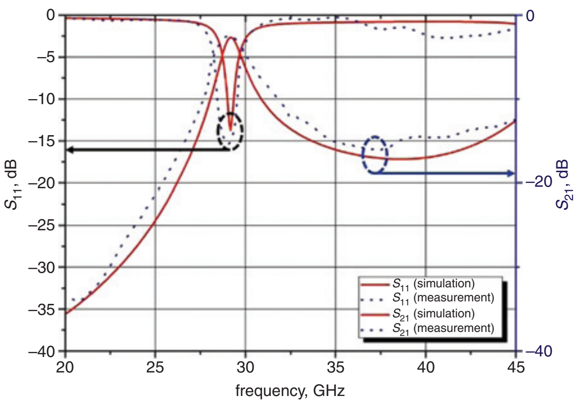

Fig. 5 *Simulated and measured S-parameters of fabricated BPF*

Conclusion: In this Letter, a K-band micromachined SIW-based filter using glass dielectric substrate with embedded metallic vias and dual inductive posts is demonstrated. The fabricated filter prototype shows an insertion loss of 2.46 dB at 29 GHz with a 3 dB bandwidth of 7.2%. The proposed filter platform is compatible with the MEMS process and provides mechanical robustness to make further direct integration of MEMS tuning devices onto it easier.

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One or more of the Figures in this Letter are available in colour online.

Ik-Jae Hyeon and Chang-Wook Baek (*School of Electrical and Electronics Engineering, Chung-Ang University, 221 Heukseok-Dong, Dongjak-Gu, Seoul 156-756, Republic of Korea*)

✉ E-mail: cwbaek@cau.ac.kr

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