A Power-Efficient Microwave Microplasma Jet Utilizing an SIW Evanescent-Mode Cavity Resonator

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***Abstract*— This paper introduces a novel 2.45 GHz microplasma jet implemented over substrate-integrated waveguide (SIW) technology. The proposed plasma jet is realized by exploiting an evanescent-mode (EVA) cavity resonator built using two separate PCB boards stacked over each other to introduce a critical gap between the two substrates around the top-center position. This allows for realizing a concentrated |E|-field in the gap for plasma formation. A capillary tube is passed right through the middle of the structure to pump helium through the critical gap area. After gas breakdown owing to the strong |E|-field in the gap with $>$ 2.7 W input power, the gas flow pushes the plasma plume out, which is up to 3-mm long with 7 slpm gas flow rate. The proposed technology is an excellent option for many applications owing to its high efficiency, planar profile, and compatibility with PCB fabrication.**

***Keywords*— Atmospheric pressure, cavity resonator, evanescent mode (EVA), plasma jet, SIW.**

I. Introduction

Low-temperature plasmas have been widely studied over the past decade because of their broad range of applications, mainly due to their impactful biological effects [1]. In one form, they can be driven out from their ignition area with the help of a background gas flow to form a plasma jet. When such a jet is exposed to the atmospheric air, it reacts with air molecules, which forms different reactive species, making it a valuable tool for various biological applications such as cancer treatment [2], blood clotting prevention [3], and wound healing [4]. However, plasma jet devices used for such applications are expensive and typically bulky and power-hungry, making them less efficient and safe.

Utilizing microwave resonators to realize microwave plasma jets is an attractive solution owing to their ability to focus, store, and efficiently reroute the EM energy, which allows for gas breakdown and hence plasma formation with much less power. Various microwave resonant structures have been reported for low-power plasma creation [5]–[7]. However, most of them are not optimal for medical applications because of not able to operate in atmospheric air.

An evanescent-mode (EVA) resonator-based plasma jet could solve the issue mentioned earlier. The EVA resonators have high-Q, can be scaled to different frequencies, and can be integrated with planar structures using substrate-integrated-waveguide (SIW) technology. Owing to their attractive features, they have been used for many applications such as impedance tuners [8], passive sensors [9], power limiters [10], frequency synthesizers [11], tunable filters [12], microwave switch [13], and tunable antennas [14]. Since the |E|-field is mainly concentrated in the gap area between the post and the cavity ceiling in an EVA cavity resonator, it also provides a proper mechanism for low-power gas breakdown. Although a copper-machined EVA-based microwave plasma jet device was introduced recently [15], the fabrication for such a device is complex and expensive because of the required micrometer precision. This paper uses SIW technology to realize a highly-efficient 2.45 GHz plasma jet. The proposed device is planar and compatible with printed circuit board (PCB) fabrication while maintaining the high-Q and requiring low input power. In addition, it could be varactor-tuned, while the device in [15] is not tunable.

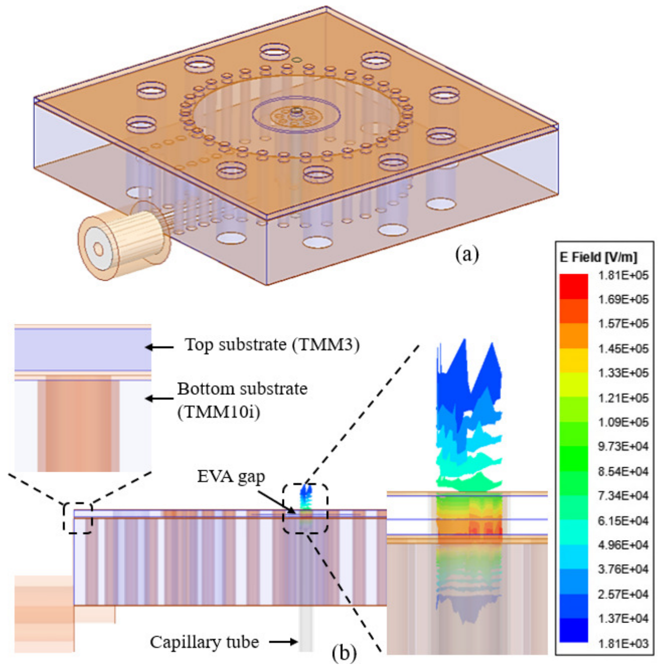

Fig. 1. (a) Schematic of the proposed 2.45 GHz EVA plasma jet implemented based on SIW technology. (b) Cross-section view of the device showing the two stacked PCB layers and the concentration of E-field in the critical gap area of the EVA resonator.

II. EVA-Based SIW Microplasma Jet

PCB-compatible devices are easy to manufacture and integrate with electrically tunable schemes using actuators [16] and varactors [17]. To develop a planar prototype for a microwave microplasma jet, SIW technology is utilized in this work, which allows for the hybrid integration

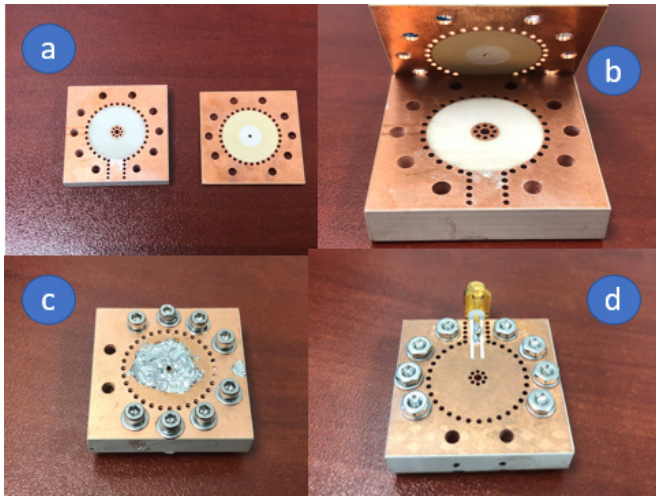

Fig. 2. Device assembly: (a) separated top and bottom substrate, (b) the top substrate is placed on top of the bottom substrate, (c) top and bottom substrates are screwed together, and (d) an SMA connector is soldered for microwave coupling.

of planar and non-planar circuits possible in single or multi-layered platforms. This scheme has already been used in designing filters and resonators [12], couplers [18], transmission lines [19], and antennas [14]. The main advantage is the compatibility with PCB technology, which reduces the fabrication complexity and makes it a low-cost and accessible solution. Moreover, the planar devices can be easily integrated with electrically tunable mechanisms.

To implement a SIW EVA plasma jet, vias are used to make the post and the cavity boundaries. A 250-mil TMM10i was used as a bottom substrate to realize the cavity, while a Rogers TMM3 of 20-mil thickness was used as a top substrate to realize the critical gap of about 0.5 mm. Figure 1 shows the device's schematic in an HFSS simulation. As observed, the electric field is mostly concentrated over the 0.5-mm gap, as expected, with a high magnitude of 1.8×10^5 (V/m) for 1-W of input power at the resonant frequency of 2.45 GHz, which guarantees low-power gas breakdown and plasma formation. As seen in Fig. 2, a central via provides the gas flow through the critical gap area by a capillary tube. The placement of TMM3 on top of TMM10i, Fig. 2(b), and assembling them with screws, Fig. 2(c), complete the EVA jet prototype in Fig. 2(d). The input feeding is done through a coplanar waveguide (CPWG) line at the bottom cladding of TMM10i, which was optimized for a 50-Ω matching. An SMA connector is connected to feed the resonator cavity as displayed in Fig. 2(d). After the assembly, a capillary tube, seen in Fig. 4, is fed through the center via, which goes up to the surface of the top substrate so that the plasma jet can interact with the atmospheric air. Helium gas is pumped into the capillary tube through a mass flow controller (MFC) to pass through the critical gap region.

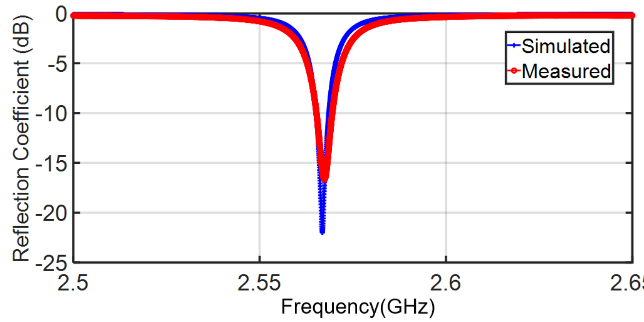

Fig. 3. The simulated and measured reflection coefficient (S_{11}) of the introduced EVA microwave plasma jet.

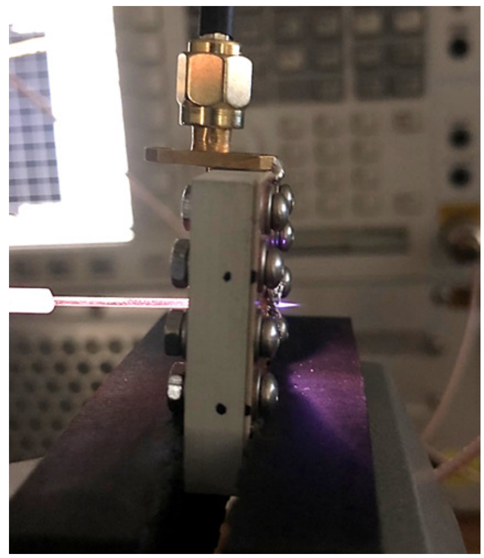

Fig. 4. The prototype SIW-based EVA plasma jet at 10 W of input power at the resonant frequency of 2.57 GHz with 7 slpm helium flow rate.

III. Results and Discussions

The prototype EVA plasma jet device was initially designed for the standard microwave plasma generation frequency of 2.45 GHz. However, after the device assembly, an undesired microgap was introduced between the two PCBs, which prevented the symmetric concentration of the E-field over the desired critical gap area, resulting in a non-uniform breakdown. This issue was addressed by introducing an additional 200-μm dielectric milling of the 20-mil substrate as a post-fabrication process, visible on the right side of Fig. 2(a) and the top side of Fig. 2(b), which caused a shift in the resonant frequency to 2.57 GHz. This change was then introduced to the simulation model and resulted in the same resonant frequency, as seen in 3. For the plasma generation test setup, the input microwave signal is generated by a signal generator, amplified with an amplifier, and fed into the structure's input port. The input and the reflected powers are measured with the help of a dual-directional coupler and two power sensors right before the plasma jet device to ensure proper power transmission to the plasma.

Figure 4 shows a sample EVA-based microwave plasma jet.

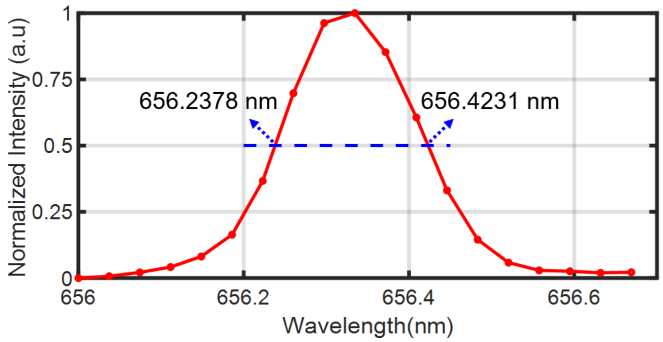

Fig. 5. Normalized H-α line in the presence of 10-W input power at 2.57 GHz and 7 slpm helium flow rate.

With 10 W of input power and a 7 slpm of helium flow rate, the jet length was about 3 mm. The gas temperature depends on the input power and remains around the room temperature for powers up to 10 W. Since the Doppler and Van der Waals broadenings of the presented device are negligible compared to the Stark broadening, the electron density of the proposed device was characterized using the Stark broadening technique of optical emission spectroscopy (OES). As the H-α profile is more distinct than the H-β profile, the full width at half maximum (FWHM) of H-α spectrum profile, shown in Fig. 5 is used to calculate electron number density (n_e) [15]. The electron density (n_e) of the presented device for 10-W of input power at 7 slpm of helium flow rate was calculated as 7.29×10^{15} cm^{-3}, which is in the same range compared to the CNC machined prototype presented by [15].

IV. Conclusion

A novel EVA cavity resonator-based microplasma jet implemented with PCB technology was demonstrated in this paper. The measured resonant frequency of 2.57 GHz and the quality factor match well with the simulated ones. The plasma is formed with $\sim$ 3.8 W of input power at 1 slpm and the jet could be sustained even with 2.7 W power at 3 slpm, representing a very low-power and efficient one. The measured electron density was in the range of 10^{15} cm^{-3}, which is considerably high for this input power range. Since electrical tunability schemes have been successfully implemented for SIW EVA resonator technology in the past, the introduced plasma jet also has the potential of being frequency tunable, giving access to a broader range of applications. The effort is in process in this regard. With an easy and low-cost PCB manufacturing process, low-power consumption, low jet temperature, and very high electron density, this plasma jet is an ideal option for many applications, especially in medicine. To pursue this aim, chemical species, specifically reactive oxygen and nitrogen species (RONS), must be precisely characterized, which is under investigation.

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Table 1. Comparison of the introduced SIW microplasma jet with other state-of-the-art 2.45 GHz resonant plasma jets.

	Input Power (W)	Electron Density (cm^{-3})	Resonator Type
[15]	> 0.5	10^{15}	EVA cavity
[20]	0.5	10^{14}	coaxial
[21]	2-10	10^{15}	coaxial
This work	> 2.7	10^{15}	SIW EVA cavity

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