Inactivation of *S. mutans* Using an Atmospheric Plasma Driven by a Palm-Size-Integrated Microwave Power Module

Seung-Jin Park, Jun Choi, Gan Young Park, Seon-Kyoo Lee, Youngsu Cho, Ji In Yun, Sangmin Jeon, Kyong Tai Kim, Jae Koo Lee, *Senior Member, IEEE*, and Jae-Yoon Sim, *Member, IEEE*

***Abstract*—A low-power palm-size microwave power module for portable microwave-excited plasma applicable to biomedicine is integrated on a single printed circuit board for the first time. The designed board includes a power amplifier chip, a phase-locked loop (PLL) chip, and an impedance matching network with microstrip lines. In addition, as a part of the true one-chip integration of the plasma power module, the PLL is designed and fabricated in a semiconductor chip with a 0.18-μm CMOS technology for dedicated use to our plasma source. For the plasma generator, a 900-MHz coaxial transmission line resonator is used with argon gas flow. The designed plasma source is applied to the inactivation of *S. mutans*, showing three-log reduction within 180-s treatment. Measurements for the different initial concentrations (from 10^5 to 10^9 CFU/mL) are also conducted, and the outcomes are discussed. The results verify the feasibility of the proposed integrated microplasma source for use in dental treatments.**

***Index Terms*—Microwave-excited plasma, nonthermal discharges, portable microplasma, sterilization, *Streptococcus mutans*.**

I. Introduction

RECENT progress of effective plasma treatment in biomedical applications has attained strong attention, leading to motivations for interdisciplinary research on the challenging field of biomedical areas [1]–[3]. The safe feature of the plasma-based treatments with charged particles and reactive species has raised expectations for possible replacement of traditional approaches which should be carefully taken due to harmful side effects. The successful outcomes with plasma treatments in soft biomedical areas, such as disinfection [4], [5], coagulation [6], and wound healing [1], have driven the development of portable atmospheric-pressure plasma sources for manufacturing point-of-care devices.

One common issue in industrial acceptance is the implementation of compact and inexpensive electrical power supply for the plasma generation. Microwave-excited microplasma has the highest feasibility compared with other types since it has the advantages of low power, low voltage, safety from high-voltage shock, electromagnetic compatibility, and long lifetime due to the low energy of striking ions. In addition, it is even nourished by the well-developed semiconductor technology for the system integration. A power amplifier (PA) chip, some oscillator circuitry, impedance matching networks on a printed circuit board (PCB), and the plasma source itself can be all integrated into a compact unit. For the microwave-excited plasma, various structures have been proposed with coaxial plasma torch [7], slot resonator [8], coaxial resonator [9], microstrip lines [10]–[12], and microstrip split-ring resonator [13]. While all these works aim at the integrated microplasma source, the true integration has not been realized until now since it still requires high level of expertise of many engineering fields.

As a promising candidate for use of the low-power and small plasma sources, site-specific disinfection has been considered for the small area treatment in dentistry [14], [15]. For the treatment of dental caries, inactivation of *Streptococcus mutans* (*S. mutans*) with an RF-powered plasma needle was demonstrated in [16]–[18]. *S. mutans* is the most significant oral pathogenic bacterium causing dental caries [19]. Traditional bactericidal treatments for *S. mutans* are based on rinsing with chemotherapeutic agents [20], [21], resulting in unwanted side effects such as stains, unpleasant taste, and lingering pain after the treatment. On the other hand, a plasma treatment is unlikely to give such pains since the bactericidal effect is due to the reactive species in the gas phase excited by plasma, presenting high feasibility as an alternative to the chemical solutions. While the effectiveness of site-specific killing of *S. mutans* by the atmospheric-pressure plasma treatment was shown in [16]–[18], quantitative measurements have not been reported yet.

This paper presents the first implementation of an integrated microwave power module on a single PCB for plasma generation and its application to the inactivation of *S. mutans* with quantitative measurements. The designed board includes a PA chip, a phase-locked loop (PLL) chip for the signal generation, and an impedance matching network with microstrip

Manuscript received November 1, 2009; revised February 26, 2010; accepted April 5, 2010. Date of publication May 24, 2010; date of current version August 11, 2010. This work was supported in part by IDEC Program of Korea for the chip fabrication, by the Korea government (MOST) through the Korea Science and Engineering Foundation Grant R01-2007-000-10730-0, and by the Korea Ministry of Education, Science, and Technology through its Brain Korea 21 Program.

S.-J. Park, J. Choi, G. Y. Park, S.-K. Lee, Y. Cho, J. I. Yun, J. K. Lee, and J.-Y. Sim are with the Department of Electronic and Electrical Engineering, Pohang University of Science and Technology, Pohang 790-784, Korea (e-mail: jysim@postech.ac.kr).

S. Jeon is with the Department of Chemical Engineering, Pohang University of Science and Technology, Pohang 790-784, Korea.

K. T. Kim is with the Department of Life Science, Pohang University of Science and Technology, Pohang 790-784, Korea.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2010.2048112

engineering. For the plasma generator, the coaxial transmission line resonator (CTLR) [9] operating at 900 MHz was adopted. Test results verify the feasibility of the proposed integrated microplasma source for clinical treatment in dentistry with an effective inactivation of *S. mutans*. Further expansion of this work to 2.45-GHz source is also underway.

This paper also describes the integration of a building block into a semiconductor chip which has never been tried for the plasma source. As the first step to the true one-chip integration of the plasma power generator, we designed our own PLL dedicated to our device. A commercial PLL chip requires an extra controller chip and complicated logics for the PLL programming, which increases cost and complexity. However, the designed PLL chip is dedicated to our microplasma source and greatly simplifies the generation of oscillating signal without the need of programming. The successful implementation of the PLL chip shows the visibility of the first single-chip integration of the microwave power module, including a PA, a PLL, and various processing logics for adaptive controls and self-calibrations.

Section II describes circuit schematics of the fabricated PLL chip, the implemented plasma source, and preparation of *S. mutans* samples. Section III discusses a brief discharge characteristics, the power efficiency of microwave-excited plasma generator, and bactericidal efficacy of the plasma. Section IV concludes this paper.

II. Description of Experimental Details

A. Power Module

Fig. 1(a) shows the schematic of the integrated plasma system. The microwave power generator consists of a designed PLL, a commercial PA (Freescale Semiconductor, MHVIC915NR2), impedance matching microstrip lines, and passive components for biasing with all integrated on a single PCB. The input to the PLL is a 56-MHz clock, which can be easily obtained with a commercial crystal oscillator. The PLL performs frequency multiplication by 16 and generates a 900-MHz signal with an output power of 9 dBm (= 8 mW). The output of PLL is applied to PA through a coupling capacitor for the isolation of dc operating conditions. The power gain can be controlled by the adjustment of Vb. The maximum output power available was 37 dBm (= 5 W). The PLL uses 1.8 V for supply voltage, and the power required for PLL operation is only 20 mW, which is negligible compared to the total power consumption. The load inductor for PA was implemented with a $\lambda/4$ 50-Ω-transmission line. The power efficiency of the power module η_{PM} can be defined as the ratio of the applied dc power on the power module and the output power. The total power to generate the maximum output power of 5 W on PA output was 15.6 W, resulting in η_{PM} of 32%. The output of PA is connected to the plasma source through a capacitor for dc blocking. For the plasma source, we used the CTLR with an input impedance of 50 Ω[9]. Since the output resistance of the used commercial PA was 10 Ω, it should be transformed to 50 Ω for the matching. The matching is performed with a cascade of three sections (Z1, Z2, and Z3) of different microstrip structures, which is typically

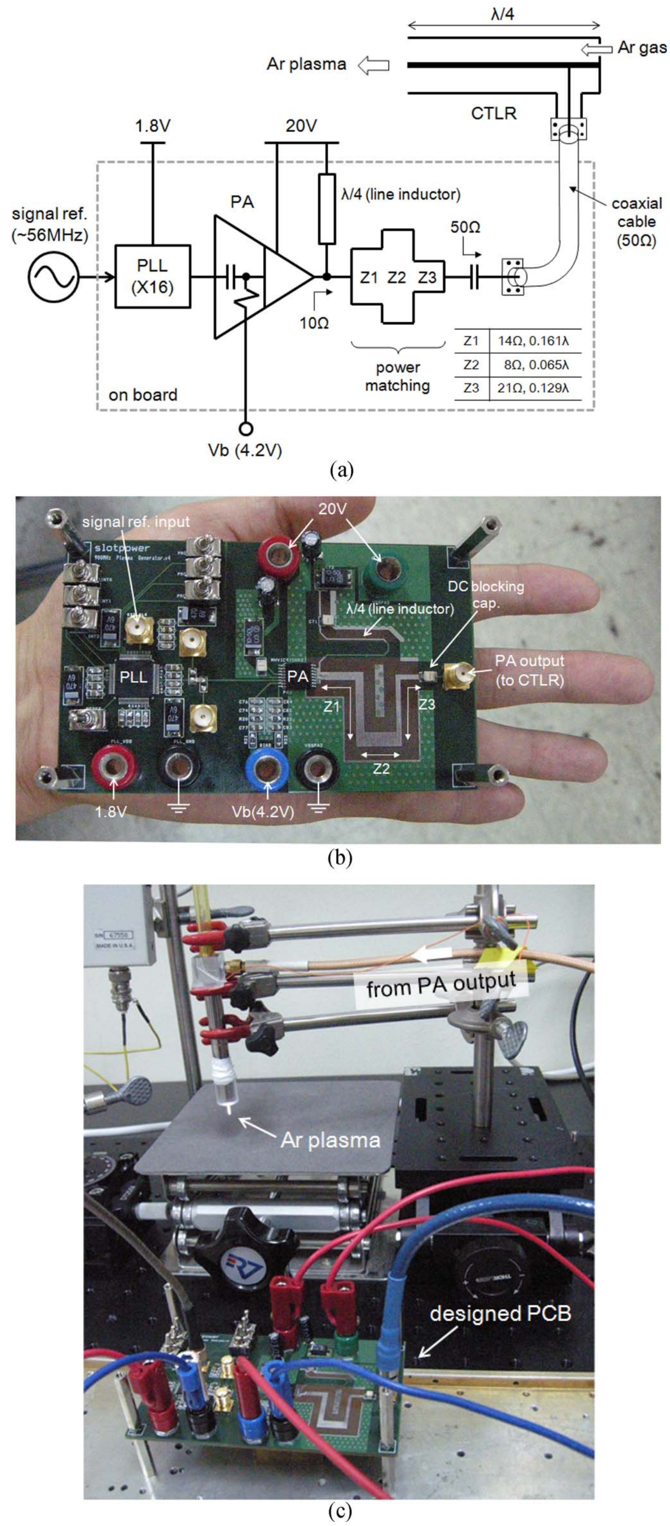


Fig. 1. Description of the integrated plasma system with (a) circuit diagram, (b) implemented power module on a PCB routing, and (c) generated plasma with a designed power module.

used for high power PA matching. Though a direct matching to 10 Ω is also possible without the matching network, it is not recommended for the following reasons. The input impedance of CTLR [9] becomes more sensitive to variations of feeding point when the target resistance is set to 10 Ω. In addition, 50 Ω gives more flexibility for various applications since the

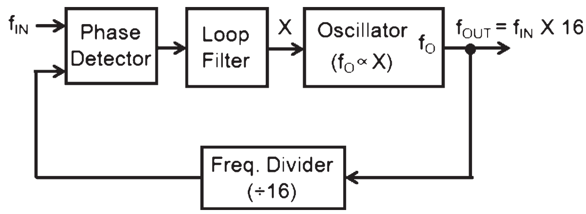


Fig. 2. Block diagram of the designed PLL (integrated into a 0.18-μm CMOS chip).

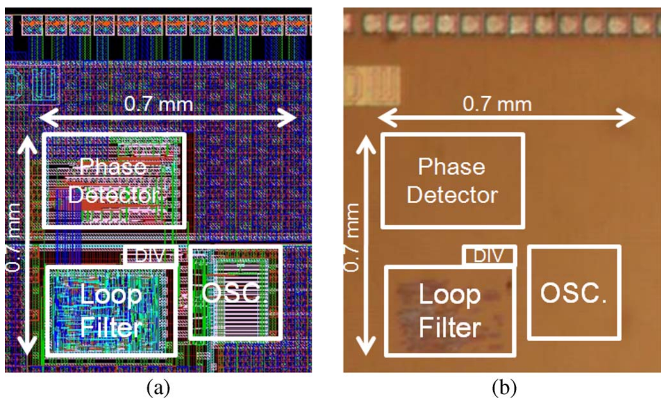


Fig. 3. (a) Layout and (b) photomicrograph of the fabricated PLL with a 0.18-μm CMOS technology. All blocks were integrated in a die size of 0.7 mm × 0.7 mm.

characteristic impedance of commercial coaxial cables and test equipment is typically 50 Ω. Fig. 1(b) and (c) shows the photographs of the designed PCB and the generated plasma with it, respectively.

It can be noted that typical commercial PA consumes significant extra power to keep high linearity, which is the most important performance in wireless communication. However, the linearity is not a concern in our plasma generation; thus, the efficiency can be further improved if a nonlinear PA is designed for the dedicated use to our application. The research on the PA design and integration into a chip is also being underway.

Fig. 2 briefly shows the circuit diagram of the designed PLL implemented in a silicon die. The PLL consists of a phase detector, a loop filter, an oscillator, and a frequency divider by 16. The phase detector compares the rising transitions of two input signals and outputs the result in the form of digital levels (one or zero). The two-level quantized digital output is smoothed out by experiencing the loop filter. Then, the filtered result on X becomes similar to an analog quantity. The ring oscillator is designed so that the output frequency should be controlled to be proportional to X. The output is fed back to the phase detector after frequency division by 16, forming a negative feedback loop for precise tracking. The frequency divider can be easily implemented by the cascade of four toggling flip-flops. The PLL was implemented in a 0.18-μm CMOS technology. Fig. 3 shows the layout and a photomicrograph of the fabricated PLL occupying a total silicon area of 0.7 mm × 0.7 mm. The tested output spectrum of the PLL is shown in Fig. 4 (Agilent, E4407B). As designed, a dominant tone is measured at a target frequency of 900 MHz. However, for the optimum S11 with CTLR, the output frequency can be precisely tuned by modifying the input frequency. Although a PLL can be

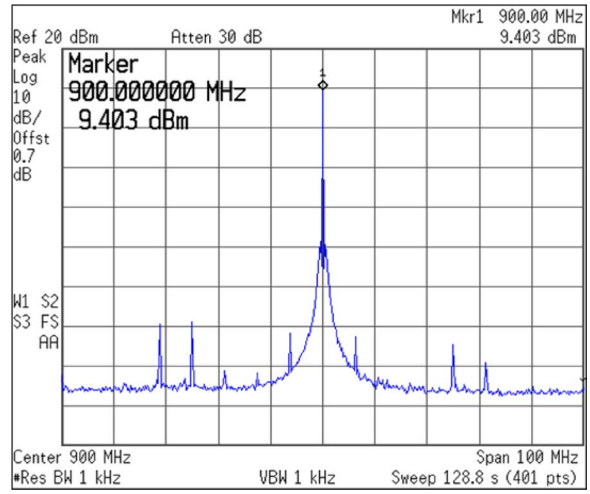


Fig. 4. Measured spectrum of PLL output with an input frequency of 56 MHz. The dominant tone is measured at 900 MHz with spurs suppressed by 60 dB.

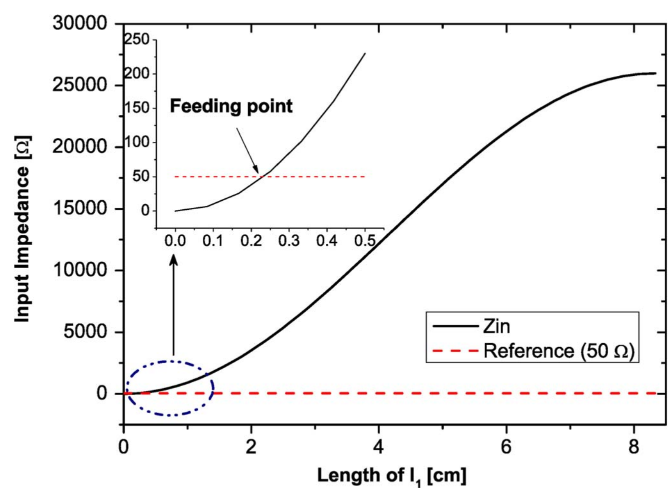


Fig. 5. Calculation of the input impedance as a function of l_1 for the CTLR and determination of the feeding point to eliminate extra matching network (the inset is the magnification of the intersecting point).

understood as a linear system, imperfections of building blocks cause some nonlinearity which generates spurs (small spikes in Fig. 4) in the spectrum. In this paper, the power of spurs is suppressed by 60 dB, which corresponds to a negligible power of microwatt range.

B. Plasma Generator

For the plasma generator, a CTLR [9] operating at 900 MHz was adopted. The device utilizes a quarter-wavelength resonance. Based on the microwave transmission line theory, the input impedance $Z_{\rm in}$ of the resonator can be calculated. The imaginary part of the input impedance disappears at a given resonance frequency of around 900 MHz. As a result, only the real part of the input impedance remains as (1), and the input impedance of the resonator is a function of feeding point, as shown in Fig. 5

$$Z_{\rm in} \approx Z_0 \left[\frac{\alpha l_1}{\sin^2(\beta l_1)} + \frac{\alpha l_2}{\cos^2(\beta l_2)} \right]^{-1} \tag{1}$$

where $l_1 + l_2 = L = \lambda/4$. L is the total length of the resonator, and Z_0 is the characteristic impedance of the coaxial transmission line. The feeding point is defined by l_1, which is the length from feeding point to short end, and l_2, which is the length from feeding point to open end. α and β represent the attenuation constant and the phase constant of the coaxial line, respectively. The complex propagation constant or wavenumber k is equal to $\beta - j\alpha$. To derive (1), it is assumed that $\alpha \cdot l \ll 1$, i.e., the loss of the transmission line is negligible, which leads to $\tan(\alpha l) \approx \alpha \cdot l$. Fig. 5 shows the plot of (1) in solid line and the reference impedance $(= 50\ \Omega)$ in dashed line. The inset in Fig. 5 shows that the two lines cross at $l_1 = 2.3$ mm, which is the optimum feeding point to eliminate extra matching networks.

C. Sample Preparation

The strain of *S. mutans* KCTC 3065/ATCC 25175 was grown in Brain Heart Infusion (BHI) broth (Fluka, Switzerland). A loopful of colonies was transferred into a 100-mL BHI medium, and an overnight culture containing approximately 10^9 CFU/mL was prepared (CFU represents colony-forming units). The cell suspension was diluted to the required concentrations of $10^5 \sim 10^9$ CFU/mL, and 50 μL of the solution was deposited onto a membrane filter and then dried. After the plasma treatment, the treated samples were placed in a 5 mL of sterile distilled water and recovered from the membrane filter using a vortex mixer. A series of dilutions were carried out; 100 μL of these dilutions was evenly spread over BHI agar plates and incubated at 37 °C for 24 h, and the colonies were counted with the number range of 30–300. All experiments were conducted in triplicate.

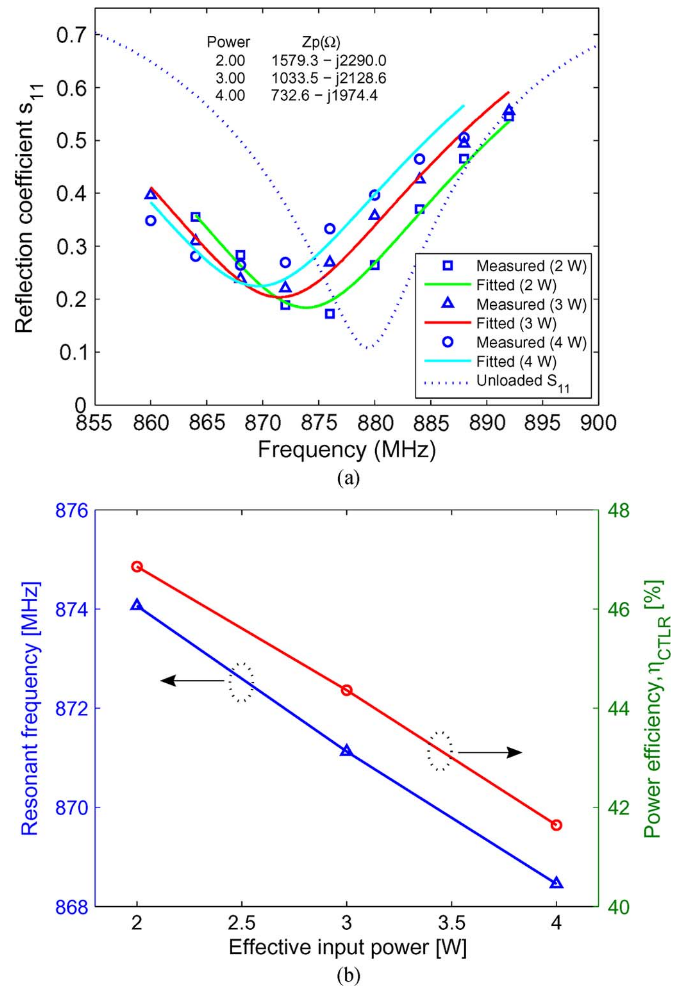


Fig. 6. Estimation of plasma impedance and power efficiency. (a) Reflection coefficient (S_{11}) before and after plasma ignition. (b) Resonant frequency and power efficiency as a function of input power.

III. Experimental Results and Discussions

A. Description of Discharge

It is suggested that the discharge is to be in nonthermal equilibrium to treat temperature-sensitive biological cells and tissues. The OH spectra at 309 nm of the discharge were investigated to estimate the rotational temperature based on the optical emission analysis [23]. The temperature in the ignition point of the plasma jet was in the range of 500–620 K for 1.5–3.5-W input power. This high temperature can contribute to the nitric oxide (NO) generation, which is one of main bactericidal agents of nonthermal plasmas. Then, the gas temperature goes rapidly down to $\sim$45 °C from the ignition point to the end of the plasma jet. Therefore, the sample bacteria *S. mutans* presented here had no thermal damage by the plasma jet. The typical value of the excitation temperature at 4-W input power and 3 standard liters per minute (slm) was shown to be ~0.45 eV, and the electron temperature was calculated to be ~1.8 eV by using a C–R model of an atmospheric-pressure argon plasma [9], [24].

B. Power Efficiency

The design of the resonator described before is biased to find out a feeding point of microwave power before igniting plasma. Once the plasma is generated at the end of the device, the behavior of the resonator is perturbed due to the capacitive nature of the charged particles of plasma. The reflection coefficient (S_{11}) of the resonator after the ignition of plasma can be measured by monitoring the forward power and reflected power. The input power of the resonator indicates the forward power minus the reflected power. The plasma impedance (Z_p) can be estimated by fitting the measured data, as shown in Fig. 6(a). The power efficiency of the CTLR itself η_{CTLR} can be calculated by using the value of Z_p. The η_{CTLR} represents the actual portion of deposited power to the plasma by the total input power delivered from the input port of the device [9].

In this paper, 4 slm of argon gas flow was applied to generate the plasma at atmospheric pressure. The deviation from the original unloaded resonant frequency increases as the input power to the devices increases. This results from the increase of the sheath capacitance due to the increase of electron density in the bulk of the discharge with increasing the input power [13]. For the input powers of 2, 3, and 4 W, the resonant frequency offsets by 5.4, 8.4, and 11.1 MHz, and the power efficiencies are reduced to 47, 44, and 41%, respectively, as shown in Fig. 6(b). Therefore, the total power efficiency of the system becomes η_{PM} times η_{CTLR}, which leads to around 14.4%.

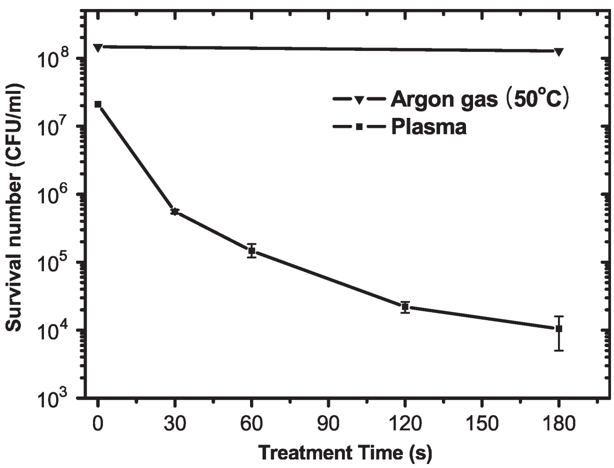


Fig. 7. Survival curve of *S. mutans* exposed to the hot argon gas (50 °C) and microwave-excited plasma jet driven by the integrated microwave power module. The input power is 4 W, the argon flow is 4 slm, and the exposure distance is 8 mm.

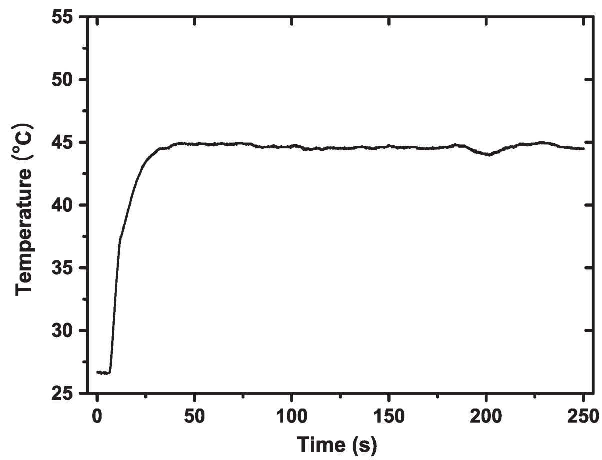


Fig. 8. Temperature of plasma plume measured at 10 mm from the nozzle for 250 s by a fiber optic sensor (FISO, FTI-10). The input power is 4 W, and the argon flow is 4 slm.

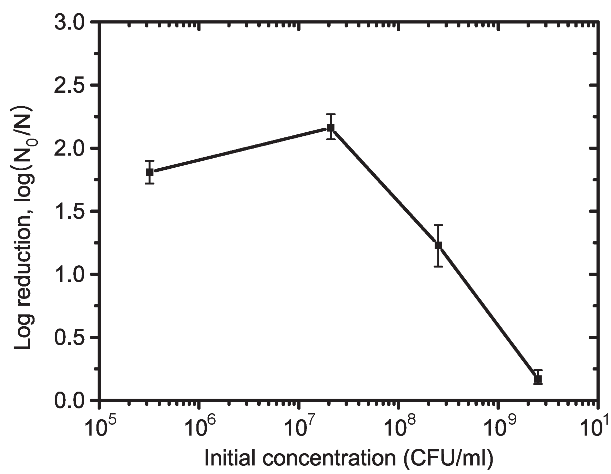


Fig. 9. Log reductions of *S. mutans* treated for 60 s with different initial concentrations. The input power is 4 W, the argon flow is 4 slm, and the exposure distance is 8 mm. (N_0 is the initial number of control cells, and N is the number of survival cells.)

C. Inactivation of S. mutans

The prepared *S. mutans* samples were exposed to the plasma jet with an input power of 4 W and an argon flow of 4 slm. The distance between the nozzle of plasma generator and a membrane filter was 8 mm. Since the length of plasma plume in this condition was about 10 mm, the plasma jet touched the cells directly. The initial concentration of *S. mutans* deposited on a membrane filter was 2.1×10^7 CFU/mL, and the 3-log reduction was achieved within 180 s, as shown in Fig. 7. The D-value that is the time required to achieve 90% reduction of microorganisms was estimated to be 19 s. The number of survivals does not follow the logarithmic function of time. The effect of the treatment decreases as the treatment time increases. After 120 s, further treatment up to 180 s did not show a significant reduction of bacteria. *S. mutans* is known to be inactivated at temperature above 60 °C [22]. To ensure that the results are not by the thermal inactivation, control experiment was also conducted with the heated argon gas (50 °C) without plasma. As shown in Fig. 7, the treatment with heated gas affects little on the viability of *S. mutans*. This reveals that the obtained inactivation results were not by the heat. It is also shown in Fig. 8 that the temperature of the plasma jet (approximately 10 mm from the nozzle) measured by a fiber optic sensor (FISO, FTI-10) for 250 s did not exceed 45 °C, revealing that the results are not by the thermal inactivation.

Fig. 9 shows the log reductions of *S. mutans* after a treatment of 60 s for the different initial concentrations. It was observed that the log reductions for the cases of 10^5 and 10^7 CFU/mL were around 2.0. However, the number drops significantly for the larger initial concentrations of 10^8 and 10^9 CFU/mL. Similar phenomenon was observed in the case of *Bacillus subtilis* spores [4]. This is because the cells in higher concentrations form a multilayered structure on the membrane filter and the top layers are likely to form a physical barrier to protect cells below them from plasma penetration. As a result, the resistance to plasma treatment is enhanced.

IV. Conclusion

A microwave power module for point-of-care plasma-driven biomedicine has been implemented on a single PCB for the first time. The designed board includes a PA chip, a PLL chip for the signal generation, and an impedance matching network with microstrip engineering. In addition, as the first step to the true one-chip integration of the plasma power module, the PLL was designed in a semiconductor chip dedicated to our plasma source. The successful implementation of the PLL chip shows the feasibility of a single-chip integration of the microwave power module. With a CTLR operating at 900 MHz for the plasma generator, the treatment was applied to the inactivation of *S. mutans*. The experimental results show three-log reduction within 180-s treatment when the initial concentration is on the order of 10^7 CFU/mL. For the larger initial concentrations of 10^8 and 10^9 CFU/mL, the bactericidal effect drops significantly, which is similar to the case of *Bacillus subtilis* spores. This is expected to be due to the multilayered structure preventing lower layers from plasma penetration. The results show the feasibility of the proposed integrated microplasma source for use in clinical treatments in dentistry.

REFERENCES

[1] G. Fridman, G. Friedman, A. Gutsol, A. B. Shekhter, V. N. Vasilets, and A. Fridman, "Applied plasma medicine," *Plasma Process. Polym.*, vol. 5, no. 6, pp. 503–533, Aug. 2008.

[2] F. Iza, G. J. Kim, S. M. Lee, J. K. Lee, J. L. Walsh, Y. T. Zhang, and M. G. Kong, "Microplasmas: Sources, particles kinetics, and biomedical applications," *Plasma Process. Polym.*, vol. 5, no. 4, pp. 322–344, Jun. 2008.

[3] G. C. Kim, G. J. Kim, S. R. Park, S. M. Jeon, H. J. Seo, F. Iza, and J. K. Lee, "Air plasma coupled with antibody-conjugated nanoparticles: A new weapon against cancer," *J. Phys. D, Appl. Phys.*, vol. 42, no. 3, p. 032 005, Feb. 2009.

[4] M. Larousii, "Low temperature plasma-based sterilization: Overview and state-of-the-art," *Plasma Process. Polym.*, vol. 2, no. 5, pp. 391–400, Jun. 2005.

[5] X. T. Deng, J. J. Shi, and M. G. Kong, "Physical mechanisms of inactivation of *Bacillus subtilis* spores using cold atmospheric plasmas," *IEEE Trans. Plasma Sci.*, vol. 34, no. 4, pp. 1310–1316, Aug. 2006.

[6] S. U. Kalghatgi, G. Fridman, M. Cooper, G. Nagaraj, M. Peddinghaus, M. Balasubramanian, V. N. Vasilets, A. F. Gutsol, A. Fridman, and G. Friedman, "Mechanism of blood coagulation by nonthermal atmospheric pressure dielectric barrier discharge plasma," *IEEE Trans. Plasma Sci.*, vol. 35, no. 5, pp. 1559–1566, Oct. 2007.

[7] R. Stonies, S. Schermer, E. Voges, and J. A. C. Broekaert, "A new small microwave plasma torch," *Plasma Sources Sci. Technol.*, vol. 13, no. 4, pp. 604–611, Sep. 2004.

[8] R. Gesche, S. Kuhn, and C. Andrei, "Plasma ignition in a quarter-wavelength microwave slot resonator," *J. Phys. D, Appl. Phys.*, vol. 41, no. 19, p. 194 003, Oct. 2008.

[9] J. Choi, F. Iza, H. J. Do, J. K. Lee, and M. H. Cho, "Microwave-excited atmospheric-pressure microplasmas based on a coaxial transmission line resonator," *Plasma Sources Sci. Technol.*, vol. 18, no. 2, p. 025 029, May 2009.

[10] J. Kim, M. Katsurai, D. Kim, and H. Ohsaki, "Microwave-excited atmospheric-pressure plasma jets using a microstrip line," *Appl. Phys. Lett.*, vol. 93, no. 19, p. 191 505, Nov. 2008.

[11] J. Kim and K. Terashima, "2.45 GHz microwave-excited atmospheric-pressure air microplasmas based on microstrip technology," *Appl. Phys. Lett.*, vol. 86, no. 19, p. 191 504, May 2005.

[12] A. M. Bilgic, U. Engel, E. Voges, M. Kuckelheim, and J. A. C. Broekaert, "A new low-power microwave plasma source using microstrip technology for atomic emission spectrometry," *Plasma Sources Sci. Technol.*, vol. 9, no. 1, pp. 1–4, Feb. 2000.

[13] F. Iza and J. Hopwood, "Split-ring resonator microplasma: Microwave model, plasma impedance and power efficiency," *Plasma Sources Sci. Technol.*, vol. 14, no. 2, pp. 397–406, May 2005.

[14] X. Lu, Y. Cao, P. Yang, Q. Xiong, Z. Xiong, Y. Xian, and Y. Pan, "An *RC* plasma devices for sterilization of root canal of teeth," *IEEE Trans. Plasma Sci.*, vol. 37, no. 5, pp. 668–673, May 2009.

[15] C. Jiang, M. T. Chen, A. Gorur, C. Schaudinn, D. Jaramillo, J. W. Costerton, P. P. Sedghizadeh, P. T. Vernier, and M. A. Gundersen, "Nanosecond pulsed plasma dental probe," *Plasma Process. Polym.*, vol. 6, no. 8, pp. 479–483, Aug. 2009.

[16] J. Goree, B. Liu, D. Drake, and E. Stoffels, "Killing of *S. mutans* bacteria using a plasma needle at atmospheric pressure," *IEEE Trans. Plasma Sci.*, vol. 34, no. 4, pp. 1317–1324, Aug. 2006.

[17] R. E. J. Sladek, S. K. Fioche, C. H. Sissons, and E. Stoffels, "Treatment of *Streptococcus mutans* biofilms with a nonthermal atmospheric plasma," *Lett. Appl. Microbiol.*, vol. 45, no. 3, pp. 318–323, Sep. 2007.

[18] X. Zhang, J. Huang, X. Liu, L. Peng, L. Guo, G. Lv, W. Chen, K. Feng, and S. Yang, "Treatment of *Streptococcus mutans* bacteria by a plasma needle," *J. Appl. Phys.*, vol. 105, no. 6, p. 063 302, Mar. 2009.

[19] R. E. J. Sladek, E. Stoffels, R. Walraven, P. J. A. Tielbeek, and R. A. Koolhoven, "Plasma treatment of dental cavities: A feasibility study," *IEEE Trans. Plasma Sci.*, vol. 32, no. 4, pp. 1540–1543, Aug. 2004.

[20] E. A. Kidd, "Role of chlorhexidine in the management of dental caries," *Int. Dent. J.*, vol. 41, no. 5, pp. 279–286, Oct. 1991.

[21] A. J. McBain, R. G. Bartolo, C. E. Catrenich, D. Charbonneau, R. G. Ledder, and P. Gilbert, "Effects of cholrhexidine gluconate-containing mouthwash on the vitality and antimicrobial susceptibility of in vitro oral bacterial ecosystems," *Appl. Environ. Microbiol.*, vol. 69, no. 8, pp. 4770–4776, Aug. 2003.

[22] Y. Ma and R. E. Marquis, "Thermophysiology of *Streptococcus mutans* and Related Lactic-Acid Bacteria," *Antonie Van Leeuwenhoek*, vol. 72, no. 2, pp. 91–100, Aug. 1997.

[23] J. Choi, A-A. H. Mohamed, S. K. Kang, K. C. Woo, K. T. Kim, and J. K. Lee, "900-MHz nonthermal atmospheric pressure plasma jet for biomedical applications," *Plasma Process. Polym.*, vol. 7, no. 3/4, pp. 258–263, Mar. 2010.

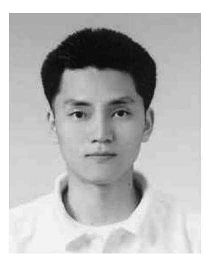
[24] X. Zhu, W. Chen, and Y. K. Pu, "Gas temperature, electron density and electron temperature measurement in a microwave excited microplasma," *J. Phys. D, Appl. Phys.*, vol. 41, no. 10, p. 105 212, May 2008.

Seung-Jin Park received the B.S. degree from the Department of Electronic and Electrical Engineering, Kyungpook National University, Daegu, Korea, in 2006. He is currently working toward the Ph.D. degree in the Department of Electronic and Electrical Engineering, Pohang University of Science and Technology, Pohang, Korea.

His interests include high-speed CMOS chip-to-chip interface circuits, DLL/PLL circuits, low-power analog circuits, and RFICs.

Jun Choi was born in Sokcho, Korea. He received the B.S. degree in electronic and electrical engineering from Chung-Ang University, Seoul, Korea, in 2003 and the M.S. degree in electronic and electrical engineering from Pohang University of Science and Technology, Pohang, Korea, in 2005, where he is currently working toward the Ph.D. degree.

His research interests include computational low-temperature plasmas, atmospheric-pressure glow discharges, and microwave-excited microplasmas for biomedical applications.

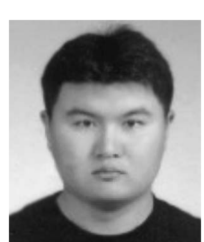


Gan Young Park was born in Korea. He received the B.S. degree in physics and the Ph.D. degree in electronic and electrical engineering from Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 2003 and 2009, respectively.

He is currently a Postdoctoral Researcher with POSTECH. His research interests include the numerical modelings and biomedical applications of low-temperature plasmas at low and high pressures.

Seon-Kyoo Lee received the B.S. degree in electronic and electrical engineering from Hanyang University, Seoul, Korea, in 2006. He is currently working toward the Ph.D. degree in electronic and electrical engineering at Pohang University of Science and Technology, Pohang, Korea.

His interests include high-speed links, PLL/DLL circuits, data converters, and low-power analog circuits.



Youngsu Cho received the B.S. degree from the Department of Electronic and Electrical Engineering, Pohang University of Science and Technology, Pohang, Korea, in 2009, where he is currently working toward the M.S. degree.

His interests include DLL/PLL circuits, ADC/DAC circuits, and RFICs.

Ji In Yun was born in Korea. She received the B.S. and M.S. degrees in microbiology from Changwon National University, Changwon, Korea, in 2004 and 2006, respectively.

She is currently an Assistant Researcher with the Pohang University of Science and Technology, Pohang, Korea. Her research interests include the mechanism study of interaction between atmospheric-pressure plasma and microorganisms.

Sangmin Jeon received the Ph.D. degree from the University of Illinois at Urbana–Champaign, Urbana, in 2002.

From 2003 to 2004, he was a Postdoctoral Fellow with Oak Ridge National Laboratory, Oak Ridge, TN. He is currently an Associate Professor with the Department of Chemical Engineering, Pohang University of Science and Technology, Pohang, Korea. He is currently on the Editorial Board of *Review of Scientific Instruments*. His main research areas are smart materials and sensors for biomedical applications.

Kyong Tai Kim received the Ph.D. degree from the University of Massachusetts, Amherst, in 1989.

From 1989 to 1991, he was a Postdoctoral Fellow with Cornell University Medical College, New York, NY. He is currently a Professor with the Department of Life Science, Pohang University of Science and Technology, Pohang, Korea. He is currently on the advisory member review of *Journal of Neurochemistry*. His research interests are focused on novel protein kinase network, biological clock genes, exo/endocytosis, and adipose tissue differentiation. He is also conducting interdisciplinary research with other expertise, including X-ray microscopy and computational modeling.

Prof. Kim is a Fellow of the Korean Academy of Science and Technology.

Jae Koo Lee (M'83–SM'02) received the Ph.D. degree from the University of California, Berkeley, in 1979.

From 1979 to 1989, he was a Senior (later a Staff) Scientist on tokamak theory with General Atomics, San Diego, CA. He is currently a Professor with the Department of Electronic and Electrical Engineering, Pohang University of Science and Technology, Pohang, Korea. He is currently on the Editorial Board of the *Journal of Physics D: Applied Physics* and *Plasma Processes and Polymers*. His research interests include the theory and simulation of low-temperature basic/processing plasmas, fusion plasmas, and free-electron lasers.

Prof. Lee is a Fellow of the American Physical Society.

Jae-Yoon Sim (M'02) received the Ph.D. degrees in electronic and electrical engineering from Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1999, respectively.

From 1999 to 2005, he was a Senior Engineer with Samsung Electronics, Yongin, Korea. In 2005, he joined POSTECH, where he is currently an Assistant Professor. His research interests include serial/parallel links, PLL data converters, and power module for plasma generation.

Prof. Sim is a corecipient of the Takuo Sugano Award at the International Solid-State Circuits Conference (ISSCC) 2001. He has served in the Technical Program Committees of the ISSCC, Symposium on VLSI Circuits, and Asian Solid-State Circuits Conference.