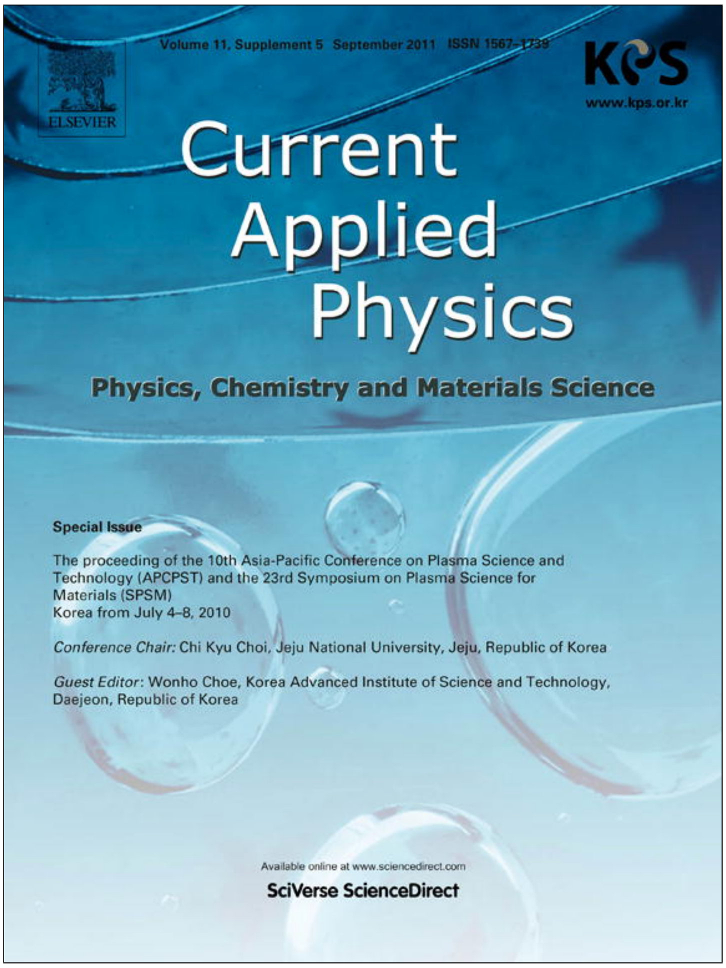
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Atmospheric pressure microplasma source based on parallel stripline resonator

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Microplasma sources with potential use in different applications can be found in the recent literature. The lifetime of most microplasma sources operating at atmospheric pressure is limited by electrode erosion due to energetic ion bombardment. These drawbacks were solved recently by several microplasma sources based on microstrip structure, which are more efficient and less prone to perturbations than other microplasma sources. This paper proposes a microplasma system source based on microwave parallel stripline resonator (MPSR), developed for the generation of microplasmas even in atmospheric air and analyzes the MPSR system with microwave field simulation via comparative study with two previous microwave sources (Microwave Spit Ring Resonator (MSRR), Microstrip Structure Source (MSS)). The result shows that the MPSR can concentrate a strong electric field of which direction is rather parallel to the stripline surface around the discharge gap, compared with other plasma sources. From the result, it is expected that the MPSR can be operated readily in low power level with high electron density because of its high strength of electric field and low plasma loss rate stemming from the parallel direction of the electric field to the stripline surface.

1. Introduction

Low pressure plasmas play a key role in many areas including electronic, aerospace, automotive, biomedical, and toxic waste management industries, and the advantages of the plasma are well known and the processing procedure is well established [1]. However, operating the plasma at low pressure has several drawbacks. Expensive vacuum systems, load locks and robotic assemblies must be used for the processing and the size of the object which is treated by plasma is also limited by the size of the vacuum chamber. Atmospheric pressure plasma can provide a critical advantage over the widely used low pressure plasma (e.g., magnetron, reactive ion etchers, capacitively coupled plasma, etc.) [2], as they do not require expensive and complicated vacuum systems. However, some problems, such as the difficulty of sustaining a glow discharge in the air, the higher voltages required for gas breakdown, and the arcing at high pressure lead to a new set of challenges in the research field. To deal with these problems, several schemes, such as dielectric-barrier discharges [3] and microwave guides plasmas (stripline, microstripline, coaxial transmission line) have been devised [4,5].

The atmospheric pressure microplasmas based on microstrip technology have been recently reported in some papers (microstrip structure plasma source, and microwave split-ring resonator) [6,7]. In these sources, a microwave power precisely fed into the target area reduces the loss to external space allowing the generation of high-density plasma. The discharge can be sustained stably over a wide range of gas pressures and the impedance matching for the discharge source can be readily conducted using simple components of microwave stripline. Its characteristic of low power operation and small discharge volume is also helpful to make integrated source of micro-portable devices. However, these plasma sources do not always provide perfect properties: it is hard to produce a large-scale plasma with high uniformity in the case of the split-ring resonators, and the voltage across the gap was not sufficiently high in the case of the microstrip structure devices [4].

In this paper, we propose a microplasma system based on microwave parallel stripline resonator (MPSR) and a comparative study with the other microwave discharge sources is performed. The design for the high frequency operation (700 MHz ~ 2.45 GHz) using resonance phenomenon allows its size to minimize. The basic design and performance of the device are a hybrid type of microwave discharge between microwave stripline source (MSS) and microwave split-ring resonator (MSRR) [4–6]. Therefore, by virtue of combination effect of each discharge source advantage, the MPSR can concentrate a strong electric field of which direction is rather parallel to the stripline around the small gap, compared with other

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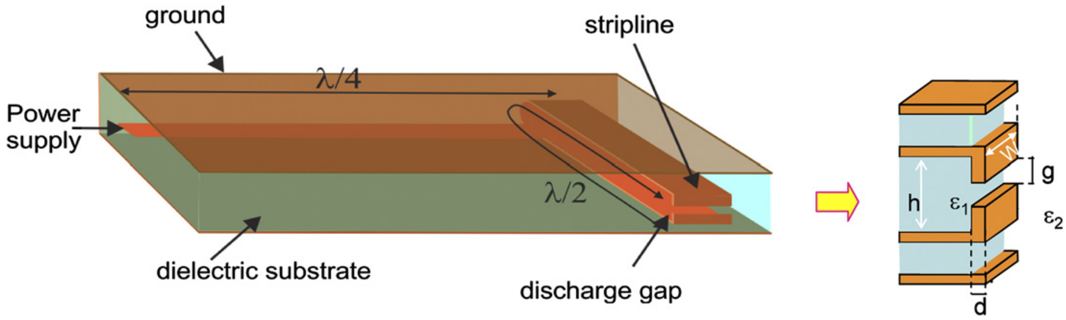

Fig. 1. The schematic of the MPSR source.

plasma sources. It is expected that the MPSR can be operated readily in low power level with high electron density because of its high strength electric field and low plasma loss rate stemming from the parallel direction of the electric field to the stripline.

2. Basics source design, analysis, and discussion

The schematic illustration of the microwave parallel stripline resonator (MPSR) source proposed in this work is shown in Fig. 1. This source consists of striplines, two ground planes, dielectric material filling the space between two ground plane, and a small discharge gap. A stripline used for the microwave matching is one-quarter wavelength wave-guide and a stripline used in resonator is a half wavelength wave-guide having two parallel arms. The plasma is generated in the small discharge gap of resonator in Fig. 1. Together with high dielectric constant material and high frequency, the systems can become a compact design suitable for the integration of micro-portable system. In our case, we can make small dimension of discharge source including matching network (1.2 cm × 1.2 cm × 0.3 cm) operating at high driving frequency $f = 2.45$ GHz using the material of high dielectric constant ($\epsilon = 9.9$). In the point of view of that the discharge source (MPSR) operates at its first odd mode of resonance, it is similar to the split-ring resonator (MSRR) having a maximum voltage difference in the device [6], and in the point of view of that the discharge is structured of microstripline, it is also similar to the microstrip structure source (MSS) [4]. Therefore the proposed MPSR source is of hybrid type of mirowave discharge source between the two previous sources (MPSR and MSS) [6].

Our analysis of the MPSR source (Fig. 1) is begun with the consideration of a global parameter, a reflection coefficient S_{11} was carried out by using commercial CST microwave studio software from Computer Simulation Technology company. As shown in Fig. 2, the S_{11} parameter spectrum has a sharp minimum value around 0.74 MHz reflecting a strong resonance of the device. A simple calculation based on Fig. 2 shows that the quality factor of the MPSR source is very high (1747), meaning the ability of the device for high efficiency discharge operation at the resonance condition.

Because of the high quality factor of the device, the precise determination of resonance frequency before the device manufacturing is very important in practice. Therefore the evolution trend of the resonance frequency with other input parameters such as the location of feeding point of input power, the characteristic stripline's impedance, and the impedance of discharge gap have to be investigated to get an insight for the discharge matching condition.

To analyze the impedance characteristics and discharge matching property of the proposed MPSR depending on the input parameters, we used a simple equivalent transmission line circuit of Fig. 3 not including the matching part. The input impedance of the MPSR is expressed as:

$$Z_{in} = Z_0 / \left[\frac{Z_0 + \frac{Z_d}{2} tanh(kl_1)}{\frac{Z_d}{2} + Z_0 tanh(kl_1)} + \frac{Z_0 + \frac{Z_d}{2} tanh(kl_2)}{\frac{Z_d}{2} + Z_0 tanh(kl_2)} \right] \quad (1)$$

where $k = \alpha + j2\pi/\lambda$ is the complex propagation constant, j is the imaginary number, λ is the wavelength at the resonant frequency, $\alpha = \pi/(Q\lambda)$ is the attenuation of the stripline, Q is the quality factor,

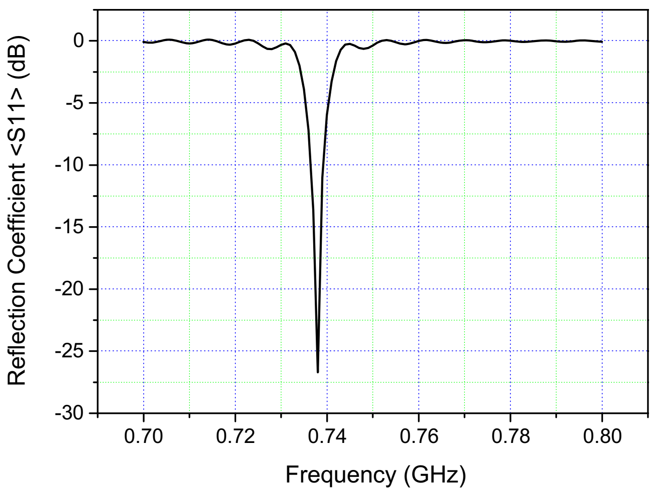

Fig. 2. The reflection coefficient (S_{11}) of the MPSR of Fig. 1 calculated from the CST microwave studio.

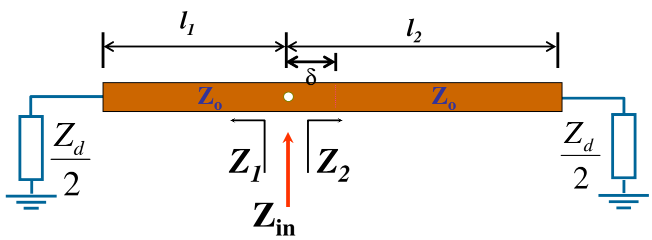

Fig. 3. The equivalent circuit of MPSR discharge source operated in an odd resonant mode (not include the matching part).

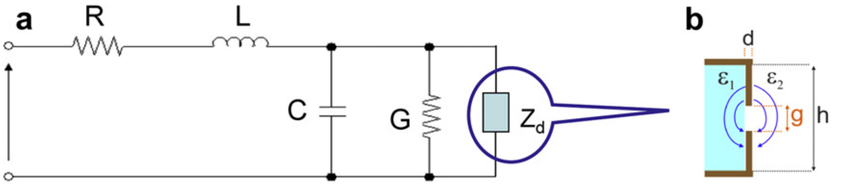

Fig. 4. The equivalent transmission circuit of MPSR discharge structure (a) and magnified view of discharge gap with simple capacitance model for calculation of resonance frequency.

Z_0 is the characteristic impedance of the stripline, and Z_d the load impedance at discharge gap. Equation (1) shows that the input impedance (Z_{in}) of the device is a function of l_1, l_2, Z_d, and Z_0, in other words, the input impedance can be changed by the position of feeding point for input power, the characteristic impedance of the stripline, and the discharge gap. However, as shown in equation (1) and previous papers [6,8], the input impedance (Z_{in}) is not a strong function of the location of feeding point of input power and the characteristic stripline's impedance, but it is a strong function of the discharge gap impedance (Z_d). Therefore, the impedance of discharge gap (Z_d) is most important factor to determine the resonance frequency, because it is the most influencing factor to the input impedance and total impedance including input impedance and matching part impedance. Furthermore, because the input impedance is mostly determined by gap width of the discharge, we can transfer our attention from "the effect of input impedance on the resonance frequency" to "the effect of discharge gap width on the resonance frequency". The influence of the discharge gap size on the resonance frequency is readily illustrated with a simple model assuming the two coplanar planes as capacitors. By applying the equation used in capacitor calculation of coplanar structure [9] to our device, the total capacitance of the discharge gap in our source can be calculated as below:

$$C_d = C_1 + C_2 + C_g = \left(\frac{\epsilon_0(\epsilon_1+\epsilon_2)}{2} \frac{K\left(\sqrt{1-\frac{g^2}{h^2}}\right)}{K\left(\frac{g}{h}\right)} + \epsilon_0\epsilon_2\frac{d}{g} \right) W \qquad (2)$$

where C_1, C_2, and C_g are the capacitances caused by left half space, right half space, and across discharge gap in Fig. 4 (b), respectively, g is the discharge gap width, W is the gap length (see Fig. 1), d is the strip thickness, h is the distance between two parallel legs of resonator, and K is the first kind elliptic integral. Together with this result of $C_{d,}$ we can calculate the resonant frequency of the device as a function of discharge gap width based on the simple model of transmission line of Fig. 4 (a) assuming $Z_d = 1/C_d\omega$ (b). The resonance frequency can be expressed as below:

$$f' = f/\sqrt{\frac{C_s'}{C_s}} = f/\sqrt{1+\frac{C_d}{C_s}} \qquad (3)$$

where f', C_s', f, C_s are the resonant frequencies and capacitances of device with and without the discharge gap, respectively. The result of dependency of resonant frequency on the gap width at the fixed thickness of the stripline (100 μm) which is calculated from equation (3) is presented in Fig. 5 (circle symbol). The resonance frequency change caused by discharge gap width change is smaller than that from CST simulation, especially in small gap size regime. These discrepancies are partly due to the contribution from two perpendicular strip legs outside the dielectric. This contribution caused a length greater than half a wavelength for the total length of resonator. The other cause probably came from the mesh densities that were not high enough, especially for the small gap size, but the result qualitatively agree well with each other.

Fig. 6 also shows the dependence of electric field strength of MPSR on the gap width. The graph shows that when the gap width reduces from 2000 μm to 500 μm the electric field at the discharge gap increases a little, but when the gap width reduces from 500 μm to 100 μm the electric field strongly increases, especially, the strength of electric field is sharply increased when the gap width is

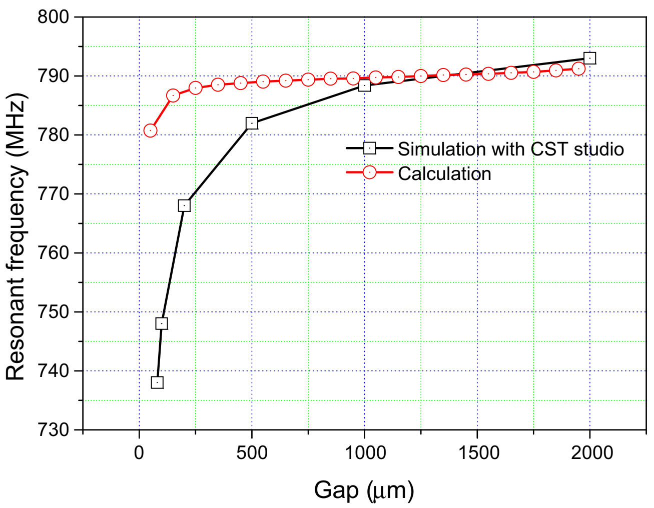

Fig. 5. The resonance frequency of the MPSR discharge source with various gap width calculated from analytic model of equation (3) (circle symbol) and CST field simulation (square symbol).

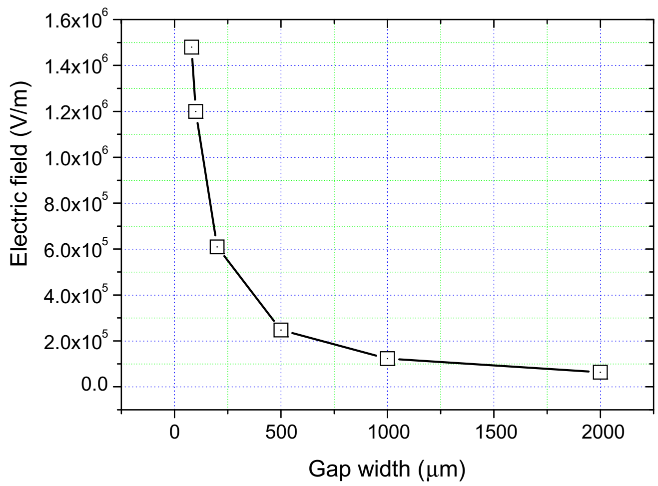

Fig. 6. The electric field of MPSR discharge source at the center of the discharge gap with various gap width calculated from the CST field simulation.

less than 100 μm. The change of electric field in the discharge gap almost agrees well with the equation $E = V/g$ with V is kept constant, where E is the electric field strength inside discharge gap, V is voltage difference across the gap, g is the gap width.

For a comparative study with previous microwave discharge sources, we also designed and run simulation for other two plasma sources with CST microwave studio as shown in Fig. 7 (a) microwave stripline structure and (b) microwave split-ring resonator. The dielectric material using in the source is a taconic of dielectric constant $\epsilon = 2.55$. The thickness of dielectric plate using in MSRR source, MSS source and MPSR source were 2 mm (MSRR, MSS) and 6 mm (MPSR), respectively. The operation frequency for three sources is 793 MHz and the gap width are 100 μm and 200 μm. The plasma can be described as an immobile dispersive dielectric material (Drude model that the electron density $n_e = 10^{12}$ cm^{-3}, electron temperature $T_e = 2$ eV and pressure $p = 760$ Torr) [10].

The results of the MPSR characteristic for the electric field strength at the discharge gap compared with those of the other two devices are summarized in Table 1. The table shows that the electric field strength generated by MPSR at the discharge gap is approximately the same level of that in MSRR, which is almost two times higher than that in MSS. Fig. 8 presents the electric field strength profiles around the discharge gap and its magnified pictures for each microwave discharge source. As shown in Fig. 8, for the case of MSRR (b), the direction of electric field around the discharge gap (not the center of the gap or the space between two electrode but around the discharge gap: see dot-box in Fig. 8) is rather perpendicular to the stripline surface, but for the case of MSS (a) and MSRR (c), the direction of electric field around the discharge gap is rather parallel to the stripline surface. It is normally a known fact that the higher electric field strength means lower ignition and sustaining voltage (power) needed, the more parallel electric field direction to the stripline surface means less plasma loss to the wall, i.e., higher plasma density [1,4]. Therefore, these results of Fig. 8 and Table 1 could inform that although MSRR seems to be the best source among these microwave plasma sources because of its highest electric field strength, the MPSR source would be the most desirable microwave discharge source having high-density plasma because of its strong electric field of which direction is rather parallel to the stripline. The MSRR and MSS could not be the most desirable microwave discharge source because of its electric field direction and strength, respectively.

In addition, similar to other microwave plasma sources, the MPSR will also present a long lifetime. Since the sheath potential is proportional to $1/\omega_{rf}^2$ assuming as a capacitively coupled plasma (CCP) source [1], the use of high frequency excitation can significantly enhance the performance of this source compare to CCP sources that are driven with RF or lower frequencies. The energy transferred to the ions in the sheath is reduced, therefore, this source is more efficient and low physical erosion.

Table 1
The simulation results of three microwave discharges.

Structure type	Characteristic impedance (Ω)	Gap width (μm)	Amplitude of electric field at the center of discharge gap × 10^6 (V/m)
Microstrip structure	50	100	0.90
	50	50	1.40
	50	100	1.10
Split-ring resonator	75	200	1.25
	75	150	2.20
	75	100	2.40
Parallel stripline resonator	75	200	1.25
	75	100	2.40

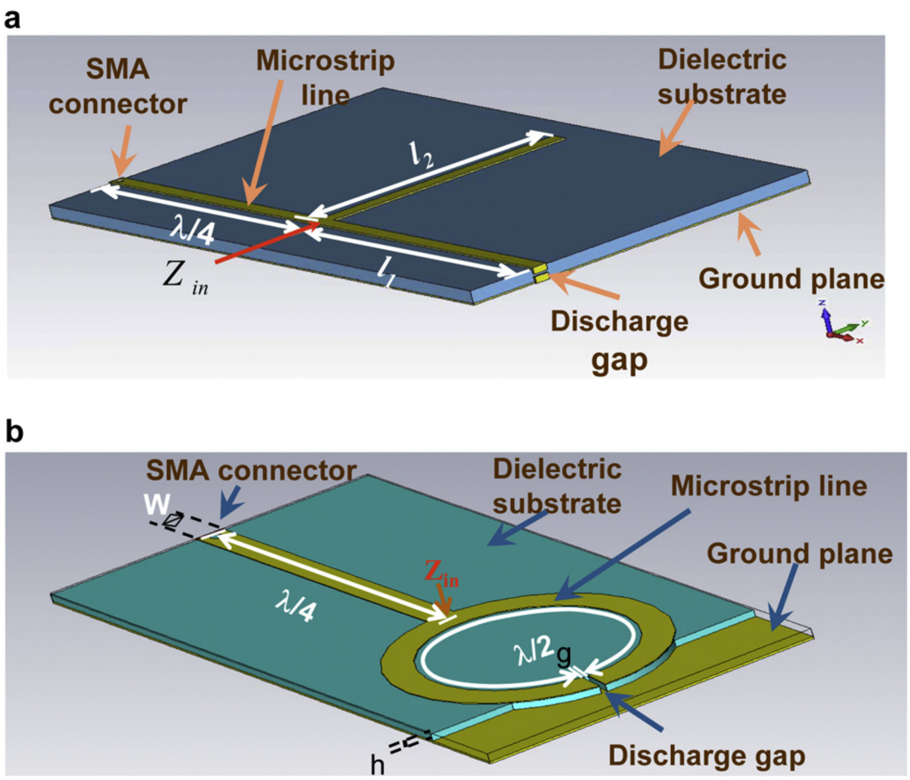

Fig. 7. Schematics of MSS source (a) and MSRR source, (b) used in the comparative study.

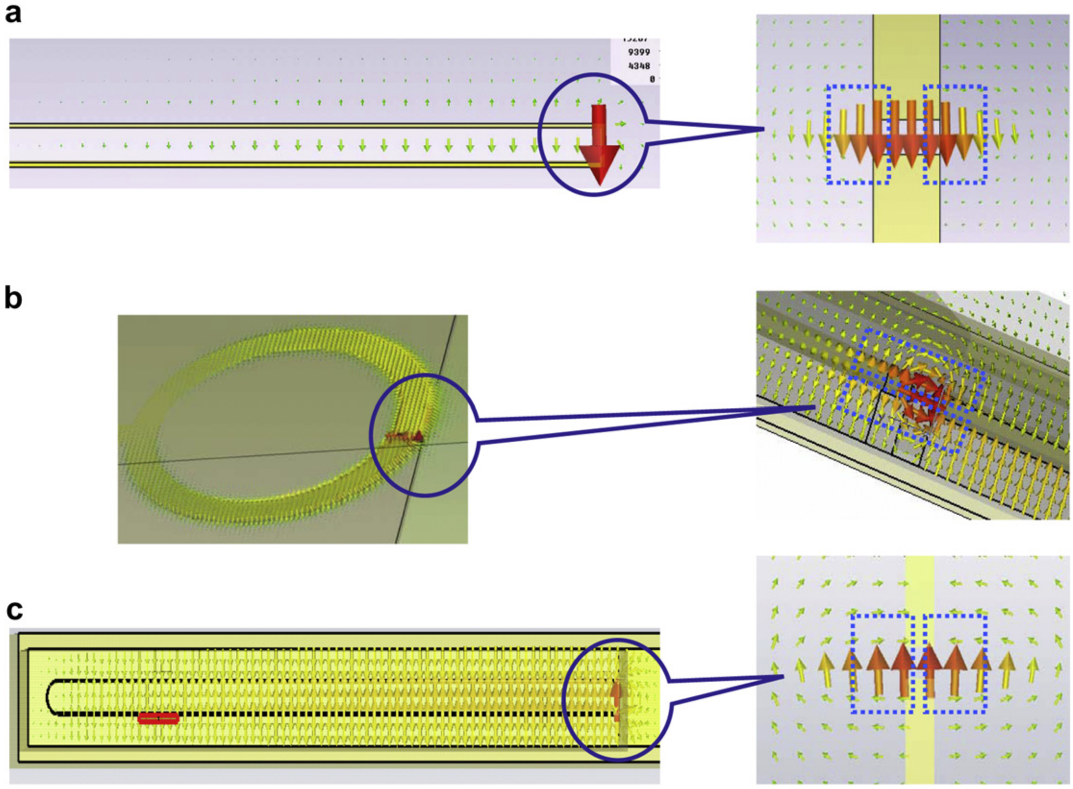

Fig. 8. The electric field profile around discharge gap for the each discharge sources: (a) MSS source, (b) MSRR source, (c) MPSR source.

3. Conclusion

In conclusion, the computer field simulation for the proposed microplasma system based on microwave parallel stripline resonator (MPSR) and the comparative study with the other microwave discharge sources revealed that the MPSR is performed as a hybrid type of two microwave discharge sources (MSS and MSRR). Therefore, by virtue of combination effect of each discharge source advantage, the MPSR can concentrate a strong electric field of which direction is rather parallel to the stripline surface around the small gap, compared with other plasma sources. It is expected that the MPSR can be operated readily in low power level with high plasma density because of its high strength electric field and low plasma loss rate stemming from the parallel direction of the electric field to the stripline surface.

References

[1] M.A. Lieberman, A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing. Wiley, New York, 1994.
[2] C. Tendero, C. Tixier, P. Tristant, J. Desmaison, P. Leprince, Spectrochimica Acta Part B: Atomic Spectroscopy 61 (2006) 2–30.
[3] U. Kogelschatz, Plasma Chemistry and Plasma Processing 23 (2003) 1.
[4] J. Kim, K. Terashima, Applied Physics Letters 86 (2005) 191504.
[5] F. Iza, J.A. Hopwood, IEEE Transactions on Plasma Science 31 (2003) 782.
[6] F. Iza, J.A. Hopwood, Plasma Sources Science and Technology 14 (2005) 397.
[7] J.J. Narendra, T.A. Grotjohn, J. Asmussen, Plasma Sources Science and Technology 17 (2008) 035027.
[8] J. Choi, F. Iza, H.J. Do, J.K. Lee, M.H. Cho, Plasma Sources Science and Technology 18 (2009) 025029.
[9] A.V. Mamishev, K. Sundara-Rajan, F. Yang, Y. Du, M. Zahn, Proceedings of the IEEE 92 (2004) 808.
[10] J.D. Jackson, Classical Electrodynamics, third ed. John Wiley & Sons, Inc., 1999.