A Miniaturized Ground Edge Current Choke—Design, Measurement, and Applications

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***Abstract*—We propose a miniaturized microwave current choke for blocking the current flowing along the edge of a substrate's ground plane. The proposed current choke is composed of a printed inductor and a printed capacitor, which possesses a size much smaller than a conventional quarter-wavelength current choke. By introducing the choke at one side of the ground plane, an effective electrical open circuit is performed for reflecting the ground edge current. The size of the proposed ground edge current choke (GECC) is as small as around 0.06 wavelength in free space. Two applications of the GECC are presented in this paper. The first is the radiation pattern regulation of a printed monopole antenna with long ground plane. The GECC in this application reflects the induced traveling-wave current along the ground plane edge and changes it to a standing-wave one, thus regulating the tilted radiation pattern due to the traveling-wave current to a broadside pattern. The other application is the decoupling of two nearby monopole antennas. By placing the proposed compact GECC in between the antennas, it is found that the isolation between the antenna ports can be enhanced from 8 dB to 32 dB. The experimental results agree well with the simulation, which demonstrate the feasibility of the proposed GECC.**

***Index Terms*—Decoupling technology, microwave current choke, monopole antenna, radiation pattern.**

I. Introduction

THE radio frequency (RF) choke is one of the important components in microwave circuits. Its function is usually known as to block the RF signal, and the general application is for supplying DC bias and preventing RF signal from leaking to the bias circuit [1]. The RF choke is usually implemented by distributed elements, such as a quarter-wavelength transmission line with short-circuited terminal, which possesses very high input impedance as an open circuit so as to stop the RF current. The function of blocking the RF signal can also be achieved by other structures, such as the defected ground (DGS) structures [2], [3] and electromagnetic band gap (EBG) structures [4]. A DGS structure performs like a low pass filter that can stop the high frequency signal and an EBG structure is like a notch filter that stops the specified frequency band.

The RF choke structures are also used in the antenna design for improving the antenna performance, such as bandwidth enhancement, multiple band operation, gain enhancement, and the radiation pattern shaping. There are already many publications discussing the use of RF chokes, DGS and EBG structures for improving antenna performance. The sleeve Balun for dipole antenna feed is a best example of using the short-circuited quarter-wavelength coaxial cable as an RF choke [5]. Similar designs were also performed in horn antennas, where the coaxial cable choke was used to prevent the current from distributing over the outer conductor of the horn [6]–[8]. These chokes mounted on the horns can improve the radiation patterns [6], [7] or enhance the antenna gain [8]. Besides, to reduce the surface wave for a good radiation pattern, the uses of ring chokes and EBG structures have been presented in [9], [10]. The concept of RF choke was also adopted to achieve multiband or wideband operation. In [11], a choke, formed by a short-circuited quarter-wavelength microstrip stub, was introduced to divide a monopole antenna into two sections so as to create two resonant paths and thus achieve dual band operation. In [12], a bandwidth enhancement technique for mobile phone antennas was developed by introducing a quarter-wavelength choke to the chassis edge. By properly designing the position of the choke, the bandwidth can be obviously improved.

In this paper, a new miniaturized RF current choke is proposed and demonstrated. Unlike utilizing a short-circuited quarter-wavelength transmission line, the proposed choke is implemented using a printed inductor and a capacitor, which is easy to be fabricated on the circuit board. And the size is as small as only 6% of the free space wavelength. As one knows, the induced ground plane current of a printed antenna (especially a small antenna) contributes to a large part of the antenna's radiation field. Also, most of the current concentrates along the edges of the ground plane. Therefore, the distribution of the ground edge current may affect the antenna's performance much. The proposed RF choke is to be located on the peripheral of the ground plane for blocking and thus shaping the ground edge current. Two applications of the choke for antenna design are presented in this study. The first is for the radiation pattern regulation. An example of a 5.25 GHz monopole antenna with a long ground plane is used to demonstrate the functionality of the choke. The second application is for reducing the coupling between two nearby monopole antennas. The enhancement of the isolation between antennas is important for a multiple-input multiple-output (MIMO) system. This paper is organized as follows. Section II presents the design and measurement of the

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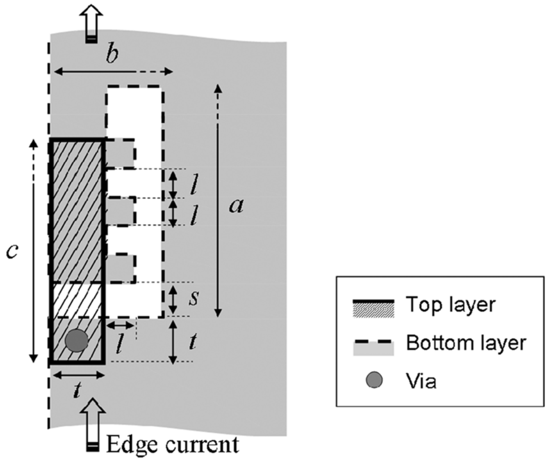

Fig. 1. Configuration of the proposed ground edge current choke.

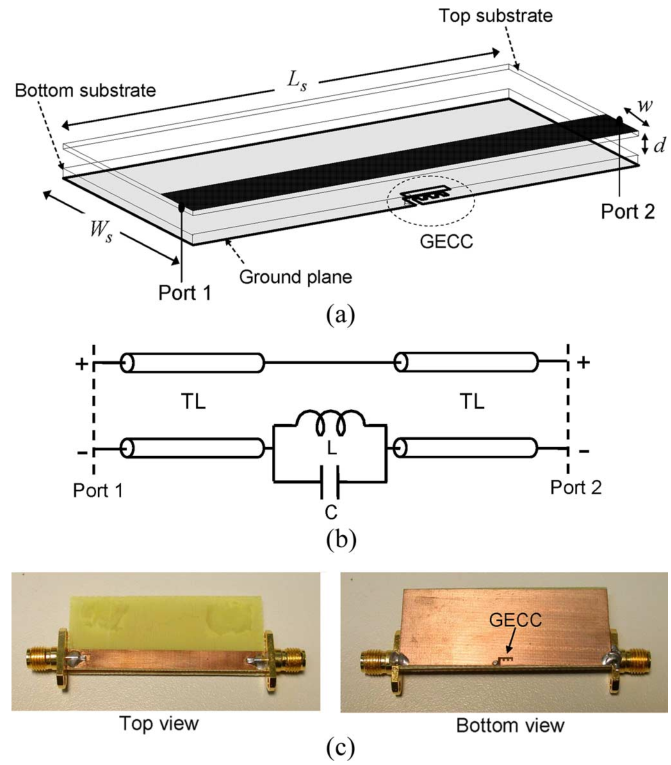

Fig. 2. (a) The transmission line structure for measuring the proposed RF choke. $L_s = 50$ mm, $W_s = 20$ mm, $w = 5$ mm, and $d = 1.6$ mm. (c) The photograph of measurement transmission line structure.

proposed choke. The two applications as mentioned above are then discussed in Sections III and IV, respectively. Section V gives a brief conclusion.

II. Design and Measurement of the Current Choke

In order to block the current traveling along ground edge, the RF choke is designed to perform an effective electrical open circuit on ground edge. Fig. 1 illustrates the geometry of the proposed ground edge current choke (GECC), which is implemented using a printed inductor and a capacitor. The inductor is realized by a corrugated L-shape slit at the ground plane edge on the bottom layer of the substrate, and the capacitor is by a metal strip on the top layer and the ground plane underneath. As shown, a via is used to connect the strip and the ground plane. When a current flows upwards along the ground edge toward the structure, part of it goes along the edge of the corrugated slit, thus experiencing an effective inductance; the rest climbs up to the metal strip through the via and is then capacitively coupled to the underneath ground plane. After that, both current streams merge and flow upwards together. Therefore, the proposed configuration forms an equivalent parallel LC resonator and thus exhibits an open circuit at the resonant frequency. The value of the capacitor depends on the overlapping area of the metal strip and the ground plane. And the length of the current path along the slit edge determines the value of inductance.

To evaluate the proposed GECC and to study the design parameters, various sets of simulations and measurements were performed. To this end, a microstrip line structure containing the proposed GECC as shown in Fig. 2(a) is proposed for test. There are two FR4 substrates used for the signal line and ground plane, respectively, to form the transmission line. The signal line is printed along the edge on the upper layer of the top substrate (with thickness of 0.4 mm). And the ground plane of the microstrip line is printed on the bottom layer of the bottom substrate (0.8 mm thickness). The GECC for testing is fabricated on the ground plane and is inserted in the middle of the ground edge just under the signal line. The equivalent circuit for this test setup is illustrated in Fig. 2(b). The current will be blocked and not go through the transmission line at the resonant frequency of the choke. By measuring the transmission coefficient (S_{21}) of the transmission line, the property of the GECC can be observed. In order to keep impedance matching, the characteristic impedance of the choke-embedded transmission line is designed as 50 Ω. From simulation, the required width of the signal line is 5 mm and the gap between two substrates is 1.6 mm. Fig. 2(c) shows the photograph of the proposed structure for measurement. Two SMA connectors are used to connect the transmission line.

The operating frequency of the GECC is designed around 5 GHz. Fig. 3 shows the frequency responses of the simulated and measured transmission coefficients (S_{21}), for various values of the GECC dimensions a, b, c. Other structure parameters are fixed as $t = 1$ mm, $l = 0.5$ mm, and $s = 0.6$ mm. Three corrugation teeth as shown in Fig. 1 are used in the L-shape slit of the GECC to provide sufficient inductance. The simulations were performed by commercial tool, Ansoft HFSS. Fig. 3(a) shows the effect of the choke length $a(= 3.5, 4.0, 4.5$ mm$)$, with choke width b and strip length c fixed at 2 mm and 3.9 mm, respectively. The measurement results agree well with the simulation. It is observed that for each length a, the frequency response exhibits a notch, with a minimum transmission coefficient of about -14 dB. The fractional 10-dB insertion-loss $(1/S_{21})$ bandwidth is about 6%. It demonstrates that the signal can be blocked by the use of the proposed GECC. The measurement notch frequencies are 5.25, 4.95, and 4.75 GHz when the length is chosen as 3.5 , 4.0, and 4.5 mm, respectively. The longer the length a, the lower the notch frequency is. This is obvious since a larger a corresponds to a longer slit and thus a longer inductive path. The increase of the GECC inductance reduces the resonant frequency

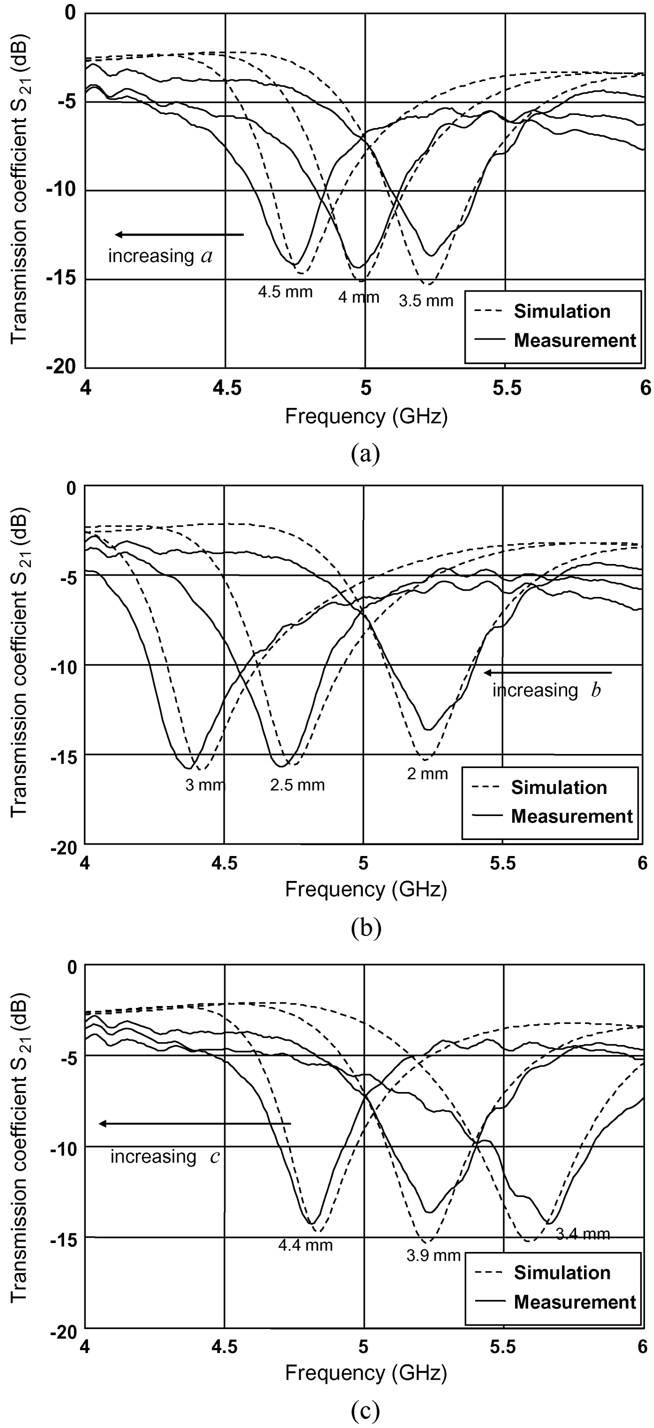

Fig. 3. Simulated and measured transmission coefficients for the GECC of various sizes. (a) Frequency responses for the chokes of different length a with $b = 2$ mm and $c = 3.9$ mm. (b) Frequency responses for the chokes of different width b with $a = 3.5$ mm and $c = 3.9$ mm. (c) Frequency responses for the chokes of different strip length c with $a = 3.5$ mm and $b = 2$ mm. Other structure parameters are fixed as $t = 1$ mm, $l = 0.5$ mm, and $s = 0.6$ mm.

of the parallel LC resonator and thus the notch frequency. Similar phenomenon can be observed when the choke width b is increased. Fig. 3(b) shows the results for various choke width $b(= 2.0, 2.5, 3.0 \text{ mm})$, with choke length a and strip length c fixed at 3.5 mm and 3.9 mm, respectively. The resonant frequency reduces from 5.25–4.375 GHz as b increased from 2 mm to 3 mm. A total frequency shift of 875 MHz is achieved for 1 mm increase of b, which is larger than that (500 MHz) for the increase of a in the same amount.

Fig. 3(c) shows the frequency responses of the transmission coefficient for various strip length $c(= 3.4, 3.9, 4.4 \text{ mm})$, with $a = 3.5$ mm and $b = 2$ mm. The resonant frequency varies from 5.7–4.8 GHz with c increased from 3.4–4.4 mm. The strip length determines the overlapping area of the metal strip and the ground, and thus affects the value of the equivalent capacitance. With the same slit size, the longer strip can has lower resonant frequency because of larger capacitance. In practice, the capacitor of the proposed GECC can be implemented in an alternative way, i.e., by using a lumped capacitor instead of a printed one. The lumped capacitor has the advantage of larger capacitance in a small size, which can be considered when further miniaturization is required.

It is seen from the above tests that, the proposed GECC structure can effectively block the ground current flowing along the edge. Its behavior is just like that of an equivalent parallel LC circuit. Although not shown here, the effects of other structure parameters have also been checked. It is found that by tuning the parameters of the corrugated slit, the equivalent inductance can be varied. And by increasing the metal strip dimensions, the equivalent capacitance can be raised. The notch frequency of the GECC can thus be controlled and designed. Note that the proposed GECC is compact as compared to others in the open literature, and has a size as small as about 0.06 wavelength in free space.

III. Application I—Radiation Pattern Regulation

The printed monopole antenna is widely used because of its simple configuration and easy fabrication. Although many structure variations have been proposed, most of the designs adopted the quarter-wavelength resonance approach. In the microwave band, the quarter-wavelength monopole antenna is small and can be easily fabricated on the same circuit board of the circuitry. For example, the monopole antenna length for the IEEE 802.11a WLAN system at 5 GHz band is only around 13 mm on an FR4 substrate. As compared to the size of the monopole radiator, the ground plane on the circuit board is usually much larger. For instance, the ground length (about 50 mm) of a small USB dongle is already near one wavelength of a 5 GHz signal. In this section, the radiation pattern of the monopole with long ground plane is to be considered with the application of the proposed GECC.

Consider a 5.25 GHz printed inverted-L monopole antenna fabricated on a 0.8 mm thick FR4 substrate, as shown in Fig. 4(a). The length L_1 and width W_1 of the substrate ground plane are 50 and 20 mm, respectively. The monopole strip is with length of $l_{m1} = 7$ mm and $l_{m2} = 6.8$ mm and width of 1.5 mm. The antenna is fed by a small section of a 50 Ω microstrip line, which, in turn, is connected to a 50 Ω coaxial cable for measurement. Fig. 4(b) shows the simulated and measured reflection coefficient (S_{11}) of the antenna. It is seen that the inverted-L monopole antenna is well matched around the center frequency. The resultant radiation patterns of co-polarization in the E plane ($y-z$ plane) at 5.25 GHz are illustrated in Fig. 5(a). Both the simulation and measurement are presented, showing

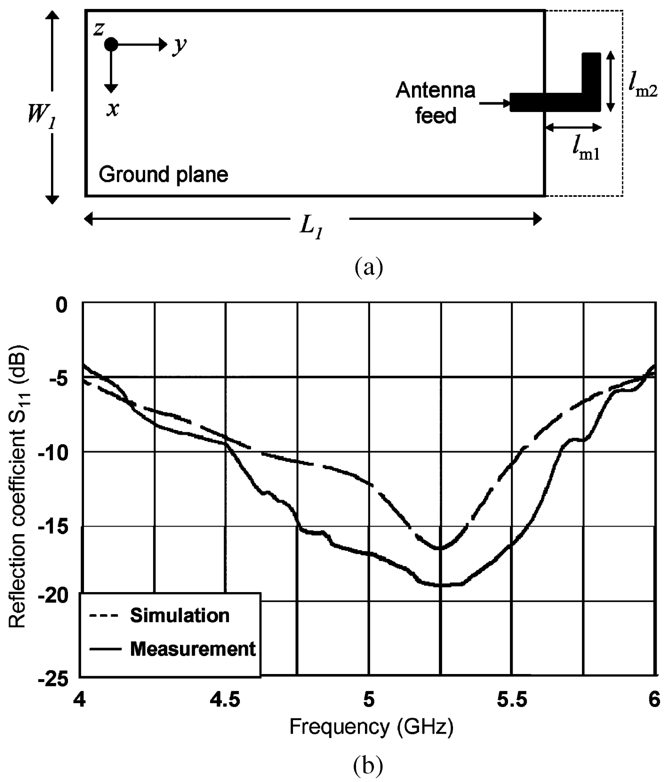

Fig. 4. (a) Structure of the inverted-L monopole antenna with long ground plane. (b) Simulated and measured reflection coefficients of the inverted-L antenna.

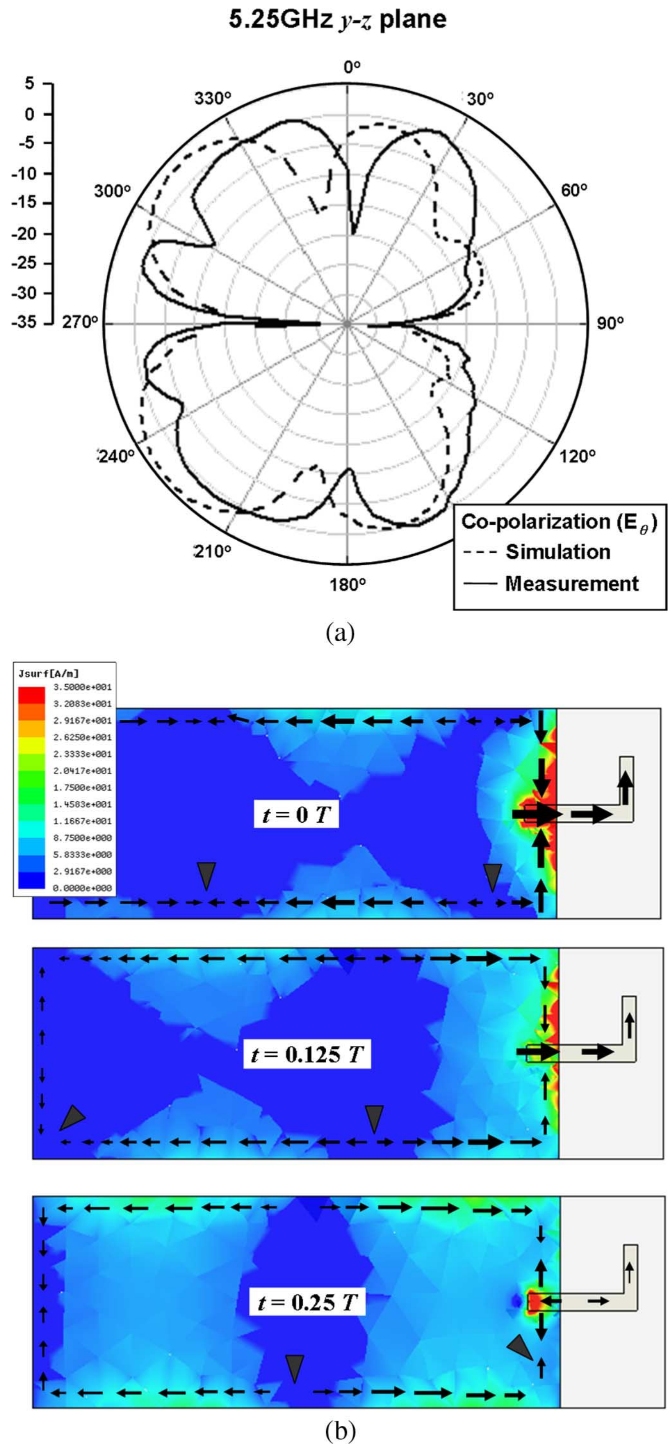

Fig. 5. (a) Simulated and measured radiation patterns of the inverted-L antenna. (b) Current distributions in different time steps of the inverted-L antenna at 5.25 GHz. T is the time period of the signal at 5.25 GHz. The arrows indicate the current null positions.

agreement with each other. It is observed that, different from a typical radiation pattern (i.e., a digit "8" pattern in the E plane) of a monopole antenna, a tilted beam is formed in the present pattern. More power is radiated toward the $-y$ direction, which is the direction of ground extension. In addition, there is a radiation null near the broadside direction. This weak broadside radiation and tilted beam pattern is not suitable for most mobile applications.

To explain the deformation of the radiation pattern, the simulated current distribution on the ground plane in different time steps is plotted in Fig. 5(b). It can be seen that the monopole radiator indeed behaves as a quarter-wavelength antenna. However, a close inspection on the ground plane current reveals that the ground current is a traveling-wave current, instead of a resonant one, propagating toward the $-y$ direction. This can be observed from the moving of the current nulls with the advance of time. The long ground plane in this case acts like a traveling wave antenna, which contributes to a radiation field toward the (current) wave-propagating direction [5]. The combination of the fields from the inverted-L monopole and the ground plane leads to the radiation pattern shown in Fig. 5(a).

To regulate the radiation pattern as a broadside radiation one, the traveling wave behavior of the ground plane current should be changed. For this purpose, the proposed GECC is designed to put at the two ground sides, as shown in Fig. 6(a). As examined in the above section, the GECCs have the function of reflecting the incident current wave so that a standing-wave current distribution may be obtained along the ground edges. The required structure parameters of the GECC for a resonant frequency at 5.25 GHz are designed as $a = 3.5$ mm, $b = 2$ mm, $c = 3.9$ mm, $t = 1$ mm, $l = 0.5$ mm, and $s = 0.6$ mm. Also, the position of the GECCs is properly chosen at $l_d = 15$ mm, which is located near the current null at $t = 0$ in Fig. 5(b). Fig. 6(b) shows the simulated and measured reflection coefficients of the inverted-L monopole antenna with a GECC-embedded ground plane. The

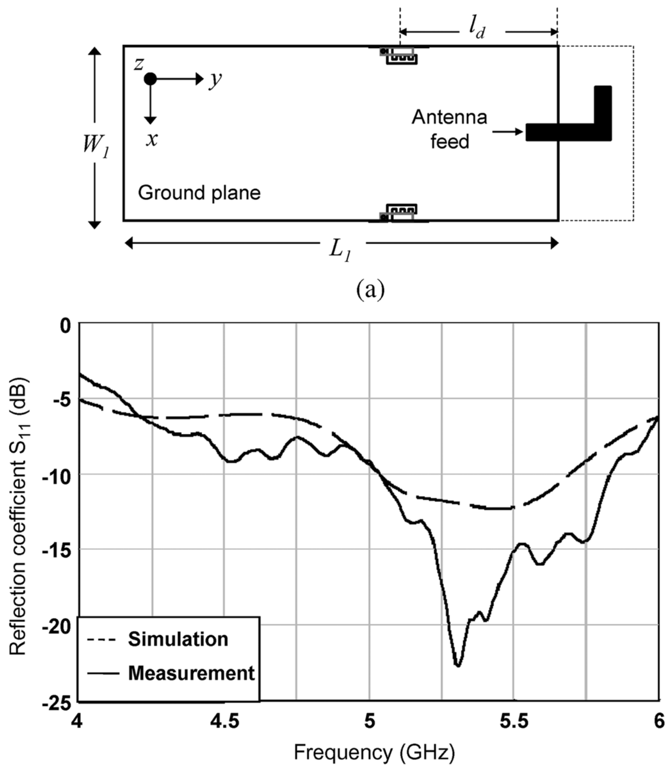

Fig. 6. (a) Structure of the inverted-L monopole antenna with GECC. (b) Simulated and measured reflection coefficients of the inverted-L antenna with GECC.

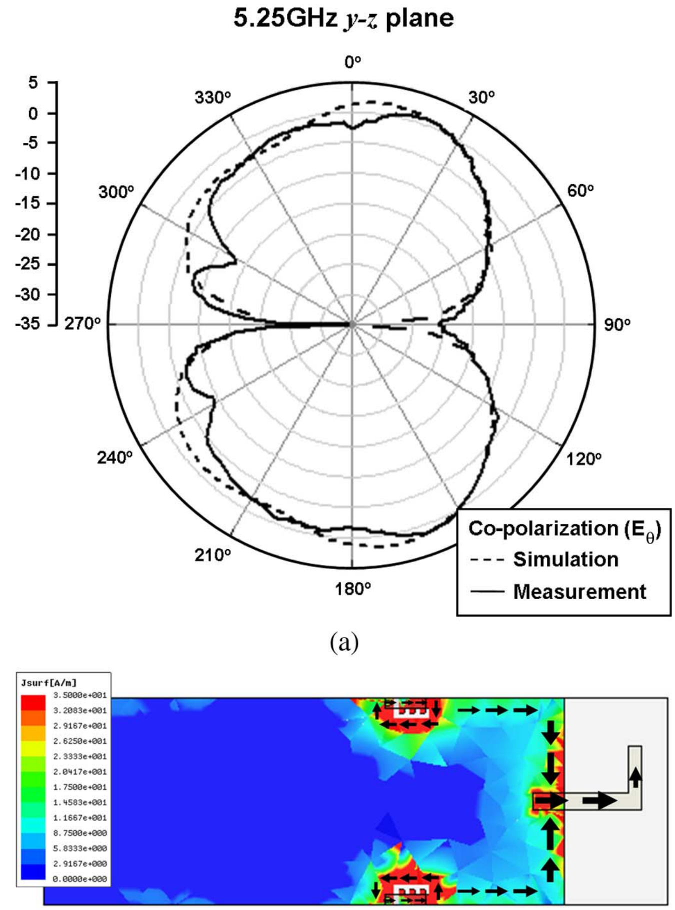

Fig. 7. (a) Simulated and measured radiation patterns of the inverted-L antenna with GECC. (b) The time-averaged current distribution combined with an instant current vector distribution on the ground plane of the inverted-L antenna with GECC.

antenna is still well matched and has a return-loss frequency response similar to that without the GECCs.

Fig. 7(a) depicts the simulated and measured radiation patterns of co-polarization in the E plane at 5.25 GHz for the GECC-embedded antenna. A significant difference is observed that the pattern becomes a digit "8" pattern that meets the expectation. The antenna pattern has changed from one with tilted beam to a broadside radiation one after the use of the GECCs. To confirm the current blocking effect of the GECCs, the time-averaged current distribution combined with instant maximum current vector are examined and plotted in Fig 7(b). The scale of the current level is the same as that in Fig. 5(b) for comparison. The current along the two sides of the ground plane has been blocked by the GECCs as expected. An effective open circuit caused by the GECC forces the current turning to be a standing wave, instead of a traveling wave, thus adjusting the radiation pattern to a broadside one.

IV. Application II—Antennas Decoupling

In this section, another important application of the GECC is revealed, i.e., the decoupling of two nearby antennas. The antenna decoupling techniques have drawn a lot of attraction in recent years because of the growing demand of multiple-antennas system. The isolation between antennas affects the performance of the communication system. Many papers have discussed the methods of diminishing the coupling between antennas. For antennas with the common ground plane, blocking the coupling ground current between antennas is one of the decoupling approaches. In [13], a fish-bone like slot on the ground plane was proposed to prevent the coupling ground current. Also, EBG structures are usually used to increase the isolation between patch antennas with common ground plane by blocking the surface wave [14].

To demonstrate the effectiveness of the proposed GECC on the enhancement of antenna isolation, let us consider two closely spaced printed inverted-L antennas operating at 5.25 GHz as shown in Fig. 8. The antennas are designed on a 0.8 mm thick FR4 substrate with the same strip width as the previous antenna but a slightly larger length for better input impedance matching. The two antennas share the same ground plane with size of $L_2 \times W_2 = 40\ \mathrm{mm} \times 90\ \mathrm{mm}$, and are separated with a distance $l_g = 12.5\ \mathrm{mm}$. Both antennas are fed by a small section of a 50 Ω microstrip line, which, in turn, is connected to a 50 Ω coaxial cable for measurement. To increase the isolation, a 5.25 GHz GECC as the previous example is placed in the middle of the two antennas on the ground edge. Fig. 9 and Fig. 10 show the measured scattering parameters of the two antennas without and with, respectively, the insertion of the GECC. As seen from Fig. 9, both the antennas are resonant at 5.25 GHz and well matched with return loss $(1/S_{11})$ better than 20 dB. However, the isolation $(1/S_{21})$ between antennas at the center frequency is only 8 dB,

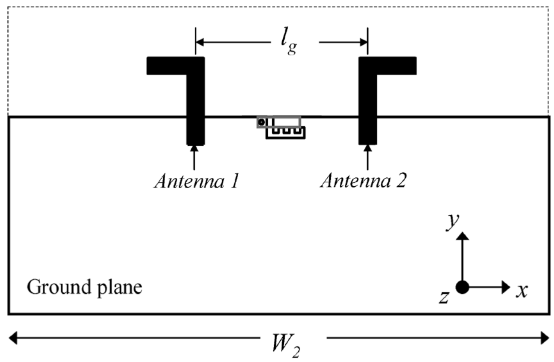

Fig. 8. Structure of two nearby printed inverted-L antennas with a GECC in between.

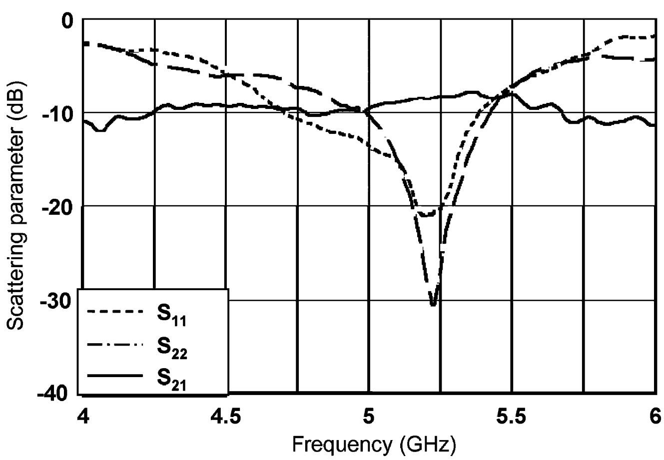

Fig. 9. Measured scattering parameters for two printed inverted-L antennas without GECC in between.

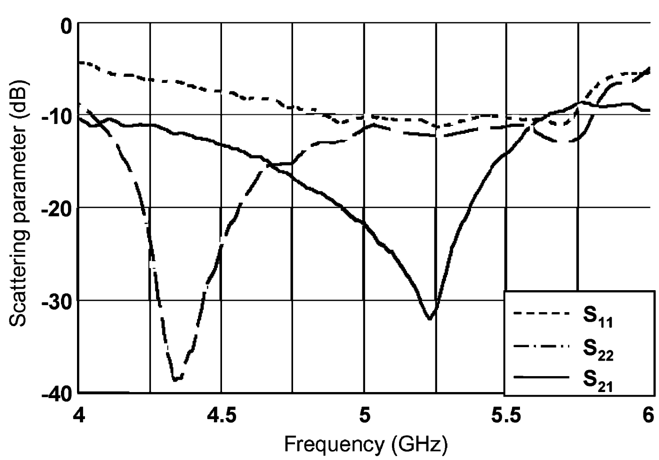

Fig. 10. Measured scattering parameters for two printed inverted-L antennas with GECC in between.

which is poor for many applications. Nevertheless, when the GECC is inserted, the isolation is greatly improved to 32 dB at 5.25 GHz as observed from Fig. 10. The isolation is better than 20 dB over the bandwidth from 4.91–5.37 GHz. The expense for the isolation improvement is the degradation of the return loss. Both the reflection coefficients of the antennas are raised in the considered frequency range, although they are still under -10 dB. (Note that the return-loss frequency responses of the two antennas are different due to the asymmetry of the GECC configuration.) If better return losses are required, the antennas need to be fine tuned or matching circuits can be used. Fig. 11 shows the time-averaged current distribution on the antennas and ground plane from HFSS simulation, when antenna 1 is fed with antenna 2 terminated. Obviously, the GECC blocks the current from antenna 1 and keeps the ground near antenna 2 silent for good isolation. Both simulation and measurement results demonstrate the decoupling ability of the proposed GECC in multiple-antenna systems.

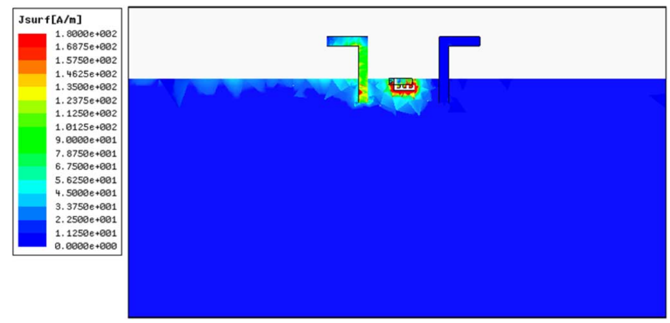

Fig. 11. The time-averaged current distribution on the antennas and ground plane when antenna 1 is fed and antenna 2 is terminated.

V. CONCLUSION

In this paper, a miniaturized ground edge current choke (GECC) and its applications have been proposed. The GECC is a parallel combination of an open slit and an overlapping strip implemented on the edge of a ground plane. The slit behaves as an inductor and the strip a capacitor. By introducing the GECC on the ground edge, an effective electrical open circuit provided by the parallel LC circuit can be performed to block the current flowing along the ground plane edge. The design and the measurement of the choke have been presented. The resonant frequency of the choke can be easily determined by the sizes of the open slit and overlapping strip. The proposed evaluation approach for the GECC by using the transmission line method has been proved effective. Two applications of the proposed GECC have been examined. The first one by using the GECC to block the traveling-wave current induced along the ground edge of a small antenna demonstrated the feasibility of the proposed structure on regulating the antenna radiation pattern. And the second application showed the ability of the GECC to enhance the isolation between two nearby antennas. The experimental results agreed well with the simulation.

The proposed printed GECC has the advantages of compact size and ease of fabrication, which can be used in more applications. For a lower operation frequency, such as 900 or 1800 MHz, the required inductance and capacitance should be increased for resonance at the design frequency. With the same size, the printed capacitor can be replaced by SMD capacitor to gain larger value for lower operation frequency. However, if only the capacitance is increased but without increasing the inductance, the fractional bandwidth might be too narrow to be used. To increasing the inductance along the current path, a magnetic material, like ferrite, may be used so as to increasing the inductance and thus the bandwidth.

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