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High-Sensitivity Ground Radiation Antenna System Using an Adjacent Slot for Bluetooth Headsets

Longyue Qu, Rui Zhang, and Hyeongdong Kim

***Abstract*—In this communication, we introduce a high-sensitivity antenna system for Bluetooth headsets dealing with the numerous and unidentified noises in a printed circuit board (PCB). This antenna system is composed of a ground radiation antenna for Bluetooth applications and an adjacent slot for noise suppression. A loop-type circuit is used to model a noise source on the PCB to provide wide-frequency spectrum noise currents to analyze the noise performance of the high-sensitivity antenna system. Decoupling between the noise sources and the antenna port can lead to high sensitivity. An adjacent slot is designed as part of the system to improve the sensitivity, based on the decoupling theorem. This proposed system is effective and applicable for high-sensitivity antenna design, as verified through simulation and active measurements of Bluetooth headsets.**

***Index Terms*—Decoupling, ground radiation antenna, high-sensitivity antenna system, noise suppression.**

I. Introduction

In wireless communication systems where good performance on indexes such as signal-to-noise ratio (SNR) and bit error rate (BER) is highly demanded, noise performance has an important impact on antenna receiving properties, especially in RF systems. The effect of noise is critical because the noise power determines the minimum signal level that can be reliably recognized by the receiving antenna [1]. For a wireless system, the noise sources are composed of intrinsic noises caused by random process in an RF receiving chip, and man-made noises coexisting in the PCB, such as digital and switching signals. In antenna design stage, the former is predetermined and fundamentally determines the intrinsic sensitivity of the receiver, which is the minimal power that can be detected by the RF chip, whereas the latter is a serious problem for antenna design that greatly degrades antenna sensitivity. The noise currents from the latter noise sources are introduced from the ground plane, which will interfere with the antenna circuit and introduce undesired signals, affecting the sensitivity of the receiving antenna. Usually, a careful PCB design is required for noise mitigation, which can be definitely of great help for antenna sensitivity and has been deeply studied in [2] and [3]. In active measurements, total isotropic sensitivity (TIS), which is strongly related to the antenna efficiency, conductive sensitivity, and noise interference, is a key parameter to evaluate the noise performance of a receiving antenna [4]. Thus, a receiving antenna can have better sensitivity by improving the antenna efficiency and/or reducing the interfering noise power. Accordingly, the antenna-related techniques, which are demonstrated in this communication, can be a supplementary practice to noise reduction problems.

There are some studies in [5]–[7], using a parasitic slot for decoupling in MIMO system where decoupled objects are identifiable and aggressive antennas. However, it has not been widely discussed how to deal with the numerous, unidentifiable, and randomly distributed noise problems where a tunable and controllable design is also necessary in practical applications. In this communication, we present a high-sensitivity Bluetooth antenna system, including a ground radiation antenna which is a small loop-type antenna that employs the ground plane as a dipole-type radiator [8]–[10], and a capacitor-loaded adjacent slot which can suppress the received noise power without affecting the characteristics of the antenna. Also, a noise source circuit is modeled to study the noise performance of the antenna system, which can be extended to the case where numerous noise sources are present in the PCB. The adjacent slot introduces different noise performance, and it can effectively be used to suppress noise sources in the Bluetooth operating band, which is the most important property in the proposed high-sensitivity antenna system. We further discuss the adjacent slot on the design principles and operation mechanisms, including the capacitor value, slot size, and location relative to the antenna. The proposed antenna system is analyzed by simulation, and the antenna property and noise performance are verified by active measurements of Bluetooth headsets in a 6 m × 3 m × 3 m three-dimensional (3-D) CTIA OTA chamber by a TC-3000B Bluetooth tester.

II. High-Sensitivity Antenna System Design

As shown in Fig. 1, the proposed high-sensitivity antenna system is designed on a simplified PCB ground plane of a Bluetooth headset that is printed on a low-cost FR4 substrate with a thickness of 1 mm and dielectric constant $\varepsilon_r = 4.4$. The ground radiation antenna is composed of a $5\ \mathrm{mm} \times 7\ \mathrm{mm}$ radiation loop terminated with a radiation capacitor C_R and a $2.5\ \mathrm{mm} \times 4\ \mathrm{mm}$ feeding loop terminated with a feeding capacitor C_F. The input impedance and the resonant frequency can easily be controlled by adjusting C_F and C_R, respectively. The ground radiation antenna and an adjacent slot constitute the two basic components of the high-sensitivity antenna system, responsible for wireless communication and noise suppression, respectively. The width and length of the slot are 1 mm and $L = 5\ \mathrm{mm}$, respectively, at an edge-to-edge distance D of 2 mm from the antenna; the open end of the slot is terminated with a capacitor C_S for sensitivity optimization. In the operating frequency of Bluetooth services, the values of C_F and C_R are chosen to be 0.45 and 0.25 pF, respectively. The value of C_S is

Manuscript received Janurary 29, 2015; revised July 28, 2015; accepted September 08, 2015. Date of publication September 24, 2015; date of current version November 25, 2015. This work was supported by the ICT R&D program of MSIP/IITP, South Korea (B0101-15-1271, Ground radiation technique for mobile devices).

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Digital Object Identifier 10.1109/TAP.2015.2481919

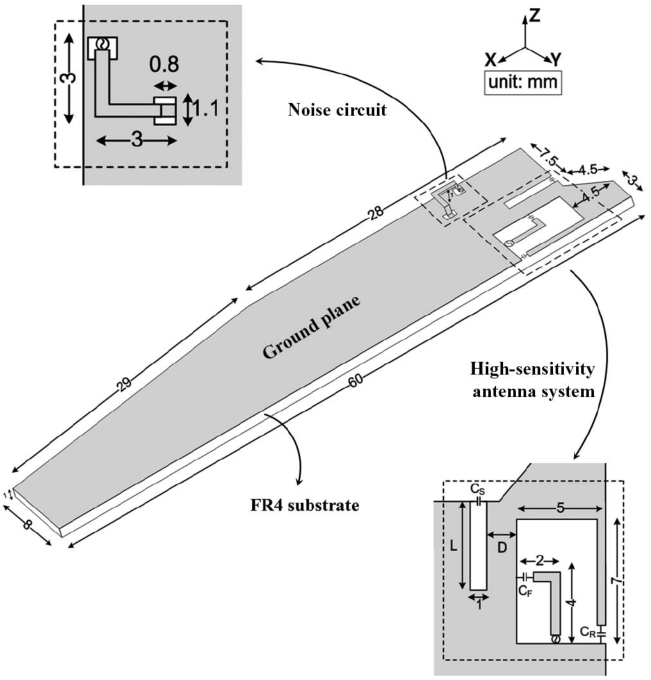


Fig. 1. Geometries of the proposed high-sensitivity antenna system in the PCB ground of a Bluetooth headset.

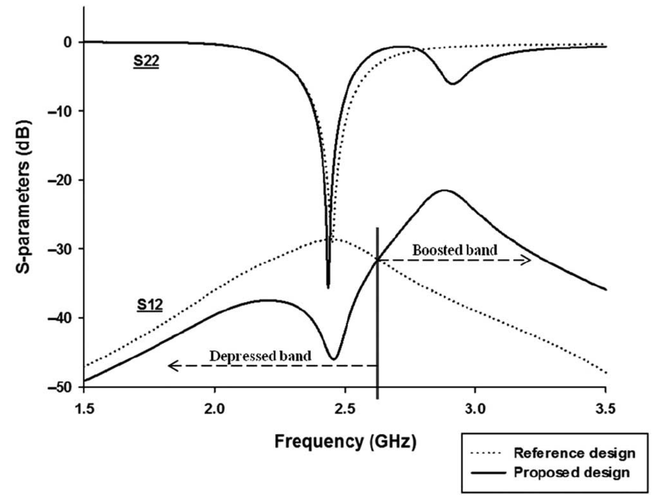


Fig. 2. Simulated results of the reference and proposed designs.

chosen to be 0.8 pF for optimal decoupling effect in simulation. Note that the antenna design without an adjacent slot is used as the reference design.

The electronic circuits in the PCB, which interfere with the antenna circuit, will act as interfering noise sources for the antenna [11]. These noise sources exist as a loop, which can be a signal trace and its return path, the bypassing loop between power and ground, or the load and its driver [11]–[13]. A loop-type circuit will be preferred as a modeled noise source, to model the current loop that the noise signal flows on. In practice, the loop-type noise circuits in a multilayer PCB exist in both two-dimensional (2-D) and 3-D shapes, relative to the ground plane. Besides, noise performance varies with the PCB designs such as bias conditions, trace direction, and component locations, which will produce noise currents in multiple directions. For simplicity, a noise source circuit, built by an L-shape 3-D circuit with 3-mm-length conductor traces in both the x- and y-axis directions at a height of 1 mm above the ground, is modeled to analyze the noise performance in the high-sensitivity antenna system. Furthermore, there exist random noise sources in different locations generated by independent noise voltages or currents [11]–[13]. Among these noise sources, this modeled noise circuit is one individual noise source in a specific location as a typical case study for noise performance, but the same method can be straightforwardly extended to the case where numerous and randomly distributed noise sources are present.

Even though the noise circuits are numerous, randomly distributed, and unidentified, the coupling between antenna and noise circuits can also be analyzed by normal network theory. In this design, the noise circuit is specified as port 1, and the antenna circuit is specified as port 2. This high-sensitivity antenna system is based on the decoupling theorem using a three-port microwave network [14]. This adjacent slot can be considered as another port, i.e., port 3. Then, the mutual impedance between the noise circuit and the antenna circuit in the presence of the adjacent slot can be represented by [15]

$$Z'_{12} = Z_{12} - \frac{Z_{13}Z_{32}}{Z_{33} + Z_L}.$$

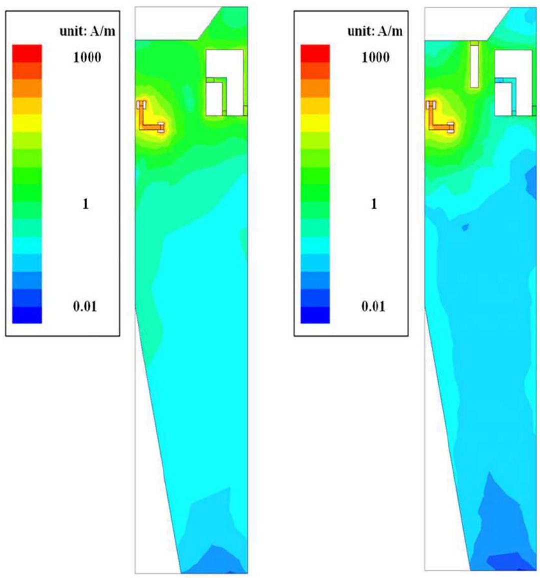
where Z'_{12} and Z_{12} are the mutual impedances with and without the adjacent slot, respectively. Z_{33} is the self-impedance observed at port 3, Z_{32} is the mutual impedance between port 2 and port 3, and Z_{13} is the mutual impedance between port 1 and port 3. Z_L is the terminated load impedance at port 3. In practice, the noise is negligible, so Z_{12} and Z_{13} are usually very small; therefore, the slot is positioned adjacent to the antenna so that Z_{32} is strong enough to have an effect on Z_{12}. By adjusting the property of the adjacent slot, $(Z_{33} + Z_L)$ is controlled such that Z'_{12} can be depressed compared to Z_{12} at a particular frequency, and can also be increased at a different frequency. This behavior can be represented by the decoupling theorem, which is verified in the following sections.

III. Simulation Analysis and Measurement Validation

The simulated scattering parameters of the reference design and proposed antenna system design are shown in Fig. 2. The −6-dB bandwidth of the proposed antenna includes 180 MHz, from 2340 to 2520 MHz, covering the Bluetooth band. The S_{12} of the reference design is as high as −28 dB at 2.45 GHz, whereas that of the proposed antenna system design is as low as −40 dB with a −45 dB null within the Bluetooth working band.

In the S_{22} curve of the proposed antenna system design, a new resonance due to the adjacent slot is observed in the higher band, compared to the reference one, showing that the resonant frequency of the slot is out of the Bluetooth working band, which is an important characteristic for maintaining antenna performance as well as providing a noise-suppressed operation. On the other hand, the antenna resonance is barely changed, and the radiation pattern is also not changed both in simulation and measurements. In the S_{12} curve of the proposed antenna system design, a coupling null is observed in the Bluetooth working band where noise level is greatly depressed, and a coupling maximum at the resonant frequency of the adjacent slot where noise level is greatly boosted. The S_{12} curve, in comparison to that of the reference design, can be divided into two parts: 1) a depressed band and 2) a boosted band. The depressed band means less interfering noise power and is desired, and the boosted band should be avoided in the working band.

According to the decoupling theorem discussed above, the slot works as a new coupling path between the antenna and noise source [16]. The latter part of the above equation cancels out the former part by tuning $(Z_{33} + Z_L)$, leading to a smaller Z'_{12} than Z_{12}; this cancelling effect is maximal at the frequency of the coupling null.



(a) (b)

Fig. 3. Simulated surface current distributions upon 2.45-GHz excitation of port 1. (a) Reference design. (b) Proposed design.

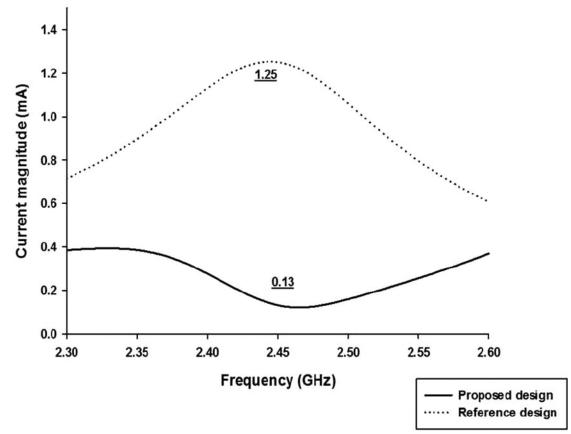
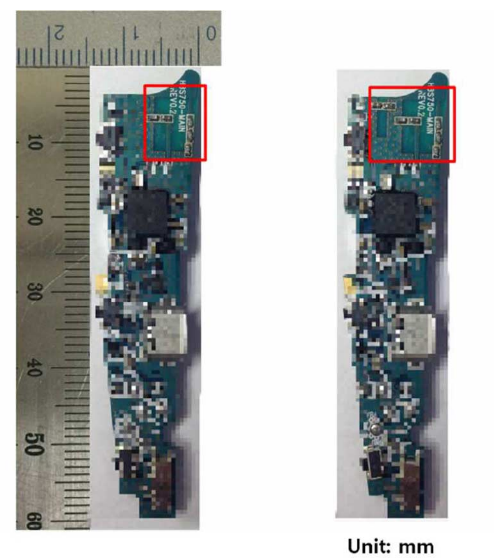


Fig. 4. Current magnitudes induced at port 2 by a unit voltage source impressed at port 1.



(a) (b)

Fig. 5. Illustration of active headset PCBs with (a) reference design and (b) proposed design.

Similarly, the latter part also boosts up the former part at other frequencies, and this is especially evident at the frequency of the coupling maximum. Therefore, the slot can be seen as a noise suppressor in band and a noise booster out of band. Also in the case of single noise source, the coupling null can be effectively used for sensitivity optimization. The different behavior of the adjacent slot in the depressed band and boosted band is an important characteristic for this proposed high-sensitivity antenna system.

For a noise source in a different place, the values of Z_{12} and Z_{13} will be changed, which means that the value of $(Z_{33} + Z_L)$ should be adjusted accordingly, i.e., it is necessary to retune the adjacent slot for ensuring the coupling null located in the receiving band while maintaining the coupling maximum out of band to avoid the antenna performance distortion. However, in the case of numerous noise source in different positions, it is impossible to optimize the coupling nulls for every single noise by tuning the adjacent slot; instead, it would be a better choice to suppress the noise sources by considering the concept of the depressed band. At a certain frequency in band, there can be greatly depressed noise sources, slightly depressed ones, undepressed ones, or/and boosted ones, but the total noise must be the result of the combination from each noise contribution at that frequency. In conclusion, the overall noise suppression can be expected by tuning the slot in an active PCB.

To verify the effect of noise suppression provided by the proposed antenna system design, the difference between the surface current distributions of the reference and proposed designs are shown in Fig. 3, in which port 1 is excited with a unit voltage source at 2.45 GHz, while port 2 is terminated with a 50-Ω load. The induced currents at port 2 of the high-sensitivity antenna system design are clearly much weaker than that of the reference design. Meanwhile, the current magnitude induced at port 2 by a unit voltage source impressed at port 1 is plotted in Fig. 4 from 2.3 to 2.6 GHz. At 2.45 GHz, the current magnitude is reduced from 1.25 mA in the reference design to 0.13 mA in the high-sensitivity antenna system design. The plots of the surface current distributions and the current magnitude indicate the effectiveness of the high-sensitivity antenna system with regard to noise suppression.

Furthermore, to see how well the proposed antenna system is performing in the implemented headsets, the active measurements are conducted, where the total radiated power (TRP) and TIS are two dominant parameters. The active headset PCBs of the reference design and the proposed antenna system design are shown in Fig. 5. The active Bluetooth headsets with each PCB are measured, respectively, for TRP and TIS specifications, in a 6 m $\times$ 3 m $\times$ 3 m 3-D CTIA OTA chamber by a TC-3000B Bluetooth tester according to the CTIA test plan [17]. The measured TIS data including low, middle, and high channels and average value are shown in Table I. By tuning the adjacent slot, an enhancement of 4.02 dB in TIS is achieved, compared to the reference TIS, when the loaded capacitor of the adjacent slot is 0.6 pF. Thus, the proposed high-sensitivity antenna system with -84.87 dBm sensitivity is 4.02 dB more sensitive than the reference design with -80.85 dBm sensitivity. Meanwhile, the TRPs of the reference design and the high-sensitivity antenna system design are 3.56 and 3.52 dBm, respectively, at a 7-dBm available transmitter power, indicating that the proposed antenna, as well as the reference antenna, is performing. Consequently, the proposed antenna system is demonstrated to be effective for noise suppression in active devices. As discussed above, the achieved high sensitivity can be a result of contribution from

TABLE I
MEASURED TIS DATA OF AN ACTIVE BLUETOOTH HEADSET

Channel	Reference design	Proposed design
0 (2402 MHz)	–79.43	–84.79
39 (2441 MHz)	–82.56	–85.14
78 (2480 MHz)	–79.88	–84.67
Average	–80.85	–84.87

TABLE II
MEASURED TIS DATA OF AN ACTIVE BLUETOOTH HEADSET FOR VARIOUS CASES

Channel	Reference design	High-sensitivity antenna system			
		$C_S = 0.2$pF	$C_S = 0.5$pF	$C_S = 0.75$pF	$C_S = 1.5$pF
0	–79.43	–82.20	–82.85	–84.79	–80.26
39	–82.56	–82.08	–83.31	–85.14	–81.76
78	–79.88	–82.31	–84.69	–84.67	–78.95
Average	–80.85	–82.20	–83.69	–84.87	–80.47

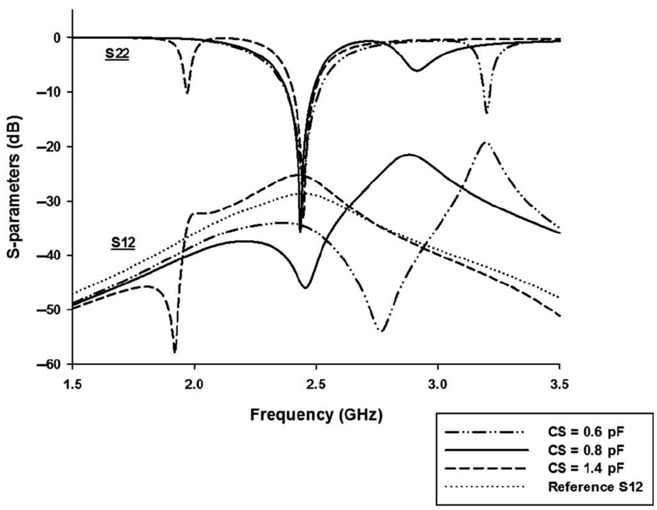


Fig. 6. Simulated parametric study: S-parameters versus frequency for various values of C_S.

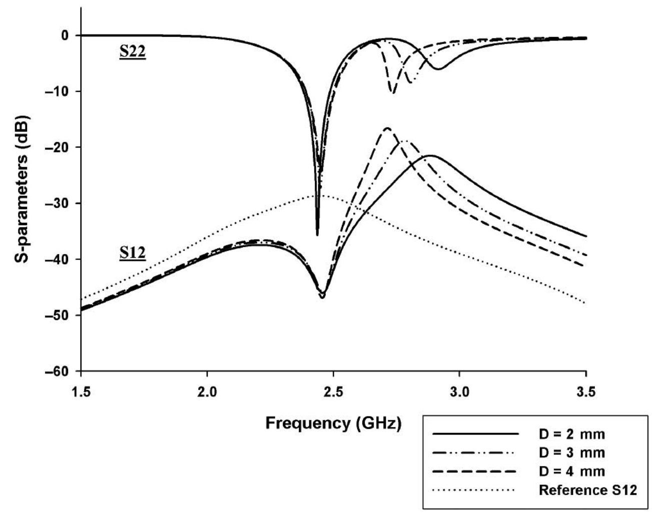


Fig. 7. Simulated parametric study: S-parameters versus frequency for various values of D.

numerous noise sources, or/and that of suppression from a dominant noise source without much effect on minor noise sources.

IV. PARAMETRIC STUDY AND DISCUSSION

The key to this proposed antenna system lies in the characteristics of the adjacent slot. For better understanding of the design principles and operation mechanisms of this antenna system, we further study the design parameters C_S, slot length L, and edge-to-edge distance to the antenna D, to see how the noise performance is affected.

A. Values of Capacitor C_S

Fig. 6 shows the regulating process performed by changing the value of the capacitor C_S. In the S_{22} curves, the second resonance, i.e., the slot resonance, can be easily controlled by varying the value of C_S. The S_{12} curves show that the coupling maximum is the same as the resonant frequency of the slot, and the coupling null and coupling maximum change simultaneously with the resonant frequency of the slot. Compared with the reference design, the proposed antenna system can achieve better sensitivity within the depressed band, and can achieve maximum level of sensitivity improvement at the coupling null. For instance, a -34 dB S_{12} is achieved at 2.45 GHz, with 6-dB improvement compared to the reference S_{12}, when the coupling null is located at 2.75 GHz with C_S of 0.6 pF. However, if the depressed band moves out of the Bluetooth band, the sensitivity can be degraded on the contrary, in the case where C_S is 1.4 pF. Note that there is little effect on the antenna characteristics in all such cases. The active Bluetooth headset with the proposed antenna system on the PCB is measured for TIS data, and the results of various C_S are provided in Table II. These measurement TIS data demonstrate that the noise performance in the proposed antenna system can behave differently with the property of the adjacent slot, so that noise suppression can be expected and sensitivity optimization can be achieved by tuning the adjacent slot. And the behavior trend provided by the measurement data validates the noise performance and analysis in simulation in the last section.

B. Edge-to-Edge Distance D

The location of the adjacent slot relative to the antenna is another critical parameter for a practical and effective antenna system. The effect of edge-to-edge distance D is shown in Fig. 7, where the separation between the coupling null and coupling maximum is shown to decrease with increasing D from 2 to 4 mm. For sensitivity optimization, the coupling nulls are maintained at 2.45 GHz by modifying the value of C_S. It is apparent that the frequency range of the depressed band is compressed due to the shift in coupling maximum, although the levels of the coupling nulls are hardly affected. Moreover, when the separation is very small, the S_{22} curves in the Bluetooth band will be affected; therefore, it is important to select the appropriate edge-to-edge distance D to maintain the antenna performance by tuning the slot resonance out of band while sustaining effective slot operation in the working band.

C. Slot Length L

The size of the slot is another important parameter for this system since it determines the characteristics of the slot itself. As in section B, the coupling nulls are again fixed at 2.45 GHz by modifying the value of C_S. As shown in Fig. 8, the separation between the null and maximum points increases as the slot length L increases from 4 to

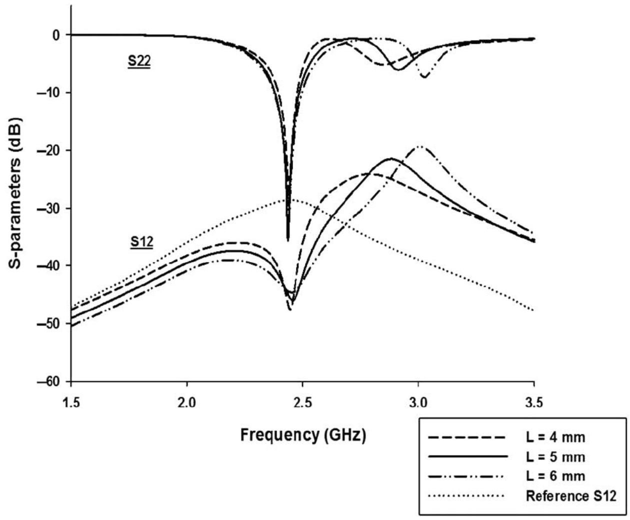


Fig. 8. Simulated parametric study: S-parameters versus frequency for various values of L.

6 mm. The entire depressed band gets wider with increasing slot length L due to the shift in coupling maximum; however, the coupling null becomes shallow. With respect to channel deviation in TIS, a larger slot is more attractive due to its wide-band decoupling effect; however, based on the TIS peak value, a smaller slot can also be useful due to its deep-level coupling null.

However, we think that much discussion remains to be studied in the noise reduction techniques, such as the effect of multiple slots, the effect of noise intensity, and the case where the coupling between the slot and noises is predominant instead of that between the slot and the antenna.

V. Conclusion

In this communication, we proposed a high-sensitivity ground radiation antenna system which is suitable for Bluetooth headsets. The two components of this proposed antenna system are a ground radiation antenna and an adjacent slot. The adjacent slot provides suppressed noise performance for the antenna in the Bluetooth working band, so that it can be used to deal with interfering noise sources for the antenna to improve sensitivity in active measurements. Compared with the reference design of an antenna without an adjacent slot, this high-sensitivity antenna system is found to be significantly effective in improving sensitivity, through simulation (an S_{12} enhancement of 17 dB) and active measurements (a TIS improvement of 4.02 dB). The design principles and operation mechanisms of the slot were discussed by considering the value of C_S, the edge-to-edge distance D to the antenna, and the slot length L. This high-sensitivity antenna system provides clearly improved sensitivity compared to a conventional reference antenna design.

Acknowledgment

The authors would like to thank RadiNa Inc. Ltd., Seoul, South Korea, for the measurement support.

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