Orientation Characteristics in the RF Electric Shielding Effects of Superconducting BPSCCO Plates

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Abstract. As one of the basic areas of research for improvement of the electromagnetic environment by use of a bulk high-critical temperature superconductor (HTS), the present paper has developed a Bi-Pb-Sr-Ca-Cu-O (BPSCCO) plate that displays orientation characteristics of the plane wave. To achieve these orientation characteristics, a slit was cut into the surface of the BPSCCO plate. The values of $SD_{EH}$ and $SD_{EP}$ are defined as the radio frequency (RF) electric shielding degrees when orienting the slit horizontal and perpendicular to the ground, respectively. The shieldings exhibit similar characteristics in the frequency region from 1 MHz (55 dB) to 100 MHz (30 dB). The values of $SD_{EH}$ in the frequency region of 100 MHz (30 dB) to 3 GHz (52 dB), increased with frequency. The values of $SD_{EP}$ indicated an average value of 30 dB in this frequency region. Namely, the difference in the RF electric shielding degree, $SD_{EH} - SD_{EP}$, with respect to the orientation of the slit, represents the orientation characteristics. Experimental results revealed several characteristics of the BPSCCO plate that include the dependencies of the orientation characteristics on the length, width, and number of slits. Also examined were the orientation characteristics in the RF magnetic shielding effect of the BPSCCO plate as a function of radio frequency.

1. Introduction
Recently, the need for a high grade electromagnetic shielding material has increased due to the increase in the electromagnetic environmental pollution. Examples of such needs are the electromagnetic shields in automobiles, medical instruments, communication devices, and robots, among others [1-3]. The present authors have developed a bulk Bi-Pb-Sr-Ca-Cu-O (BPSCCO) plate that displays orientation characteristics in the RF magnetic shielding effects of a plane wave, as one of the basic areas in the research for improvement of the electromagnetic environment. This was achieved by use of a bulk, high-critical temperature superconductor (HTS), which employs perfect diamagnetism and conductivity, as an ideal material for use as an RF shield [4-8]. However, the orientation characteristics found in the RF electric shielding effects of the BPSCCO plate had been unknown until now. To examine these characteristics, a slit was cut on the surface of a BPSCCO plate; hereafter termed the slit BPSCCO plate. The RF electric shielding degrees $SD_{EH}$ and $SD_{EP}$ are measured when the slit is oriented horizontal and perpendicular, respectively, and exhibit similar shielding characteristics in the frequency region from 1 MHz (55 dB) to 100 MHz (30 dB). The values of $SD_{EH}$ then increased with frequency over the range from 100 MHz (30 dB) to 3 GHz (52 dB), while those of $SD_{EP}$ indicated an average value of 30 dB in this frequency region. That is, the difference between $SD_{EH}$ and $SD_{EP}$ represents the orientation characteristics. It is anticipated that those orientation characteristics can be used in new applications such as the switch for a microwave guide, in a low
noise antenna to achieve greater directivity, and as a filter for radio frequency bands, among others.

Experimental values of $SD_{\text{EH}}$ and $SD_{\text{EP}}$ revealed the dependencies of orientation characteristics on the length, width, and number of slits. It is, also, included the orientation characteristics in the RF magnetic shielding effects $SD_{H}$ for the slit BPSCCO plates as a function of radio frequency.

2. Experimental procedure

In the present research, a commercial BPSCCO plate (Toshima, Lot. 7805-01, 50 mm square, 4 mm thick) was used. A slit (42 mm in length $L$, 1 mm in width $w$) was cut all the way through the BPSCCO plate with a diamond saw at low cutting speeds to inhibit any heat effects and to prevent cracking, as was reported in [8, 9]. In order to facilitate a systematic investigation of the orientation characteristics of the RF electromagnetic shielding degree as related to the slit length $L$ of the BPSCCO plate, use was made of plates with various slit lengths $L$ between 0 mm (no slit) and 42 mm. In addition, BPSCCO plates with slit widths $w$ between 1 mm and 11 mm were used. Use was also made of plates having width $w > 1$ mm with slits numbering $N$ of between 1 and 11 in order to clarify the orientation characteristics.

A scanning electron microscope (SEM) photograph of the surface of the BPSCCO plate is shown in Fig. 1. It can be seen that the BPSCCO plate consists of a porous surface structure, with a BPSCCO grain size between approximately 10 – 30 µm. Typical X-ray diffraction measurements of the BPSCCO plate were then carried out in order to analyze the crystallographic structure. The X-ray source was copper K$_\alpha$, and the diffraction pattern of the BPSCCO plate was obtained, such as shown in Fig. 2. It was found that the Bi-2223 phase appeared clearly in the plate. Furthermore, the critical temperature $T_c$ for this BPSCCO plate was determined as approximately 110 K.

For evaluation of the shielding degree of a plane wave, an experimental system was used to measure the orientation characteristics of the slit BPSCCO plates, such as was reported in Refs. [7–9]. The RF output of the tracking generator, equipped with a spectrum analyzer (HP, 8594E), was amplified by 50 dB with the use of a broadband amplifier (Kalmus, 210LC-CE), and guided to a transmitting antenna in a metal cell, then transmitted through the slit plate to the receiving cell. The signal from the receiving antenna was amplified by 38 dB by a preamplifier (Sonoma, 317), and then guided to the input terminal of the spectrum analyzer. In this arrangement, the coaxial cable employed as the receiving line was threaded through ferrite rings, in order to reduce any interaction between the transmitting and receiving lines [4–9]. In addition, probe and loop antennae were employed for measuring the RF electric and RF magnetic shielding effects, respectively.

The RF electric shielding degree $SD_{E}$ can be calculated as follows, being defined in terms of the reduction in the electric field that occurs due to the shielding material [10]. In the present research, the
value of $SD_E$ is defined as $SD_E = 10 \log_{10} (P_{E0}/P_{E1})$. Here, $P_{E0}$ and $P_{E1}$ are the incident electric field power and that of the transmitted wave as it emerges from the shielding plate, respectively. The value of the RF magnetic shielding degree $SD_H$ is also determined by $SD_H = 10 \log_{10} (P_{H0}/P_{H1})$. Here, $P_{H0}$ and $P_{H1}$ are the output of the magnetic field power of the receiving antenna, with and without the BPSCCO plate, respectively. The values of $SD_E$ for the horizontal- and perpendicular-oriented slit plates are termed $SD_{EH}$ and $SD_{HP}$, respectively. On the other hand, $SD_{HH}$ and $SD_{HN}$ are the values of $SD_H$ when holding the slit in the horizontal and perpendicular, respectively.

### 3. Results and discussion

#### 3.1. RF electric shielding effects of the slit BPSCCO plate

Figure 3 shows the characteristics of the RF electric shielding degree $SD_E$ for the non-slit and slit (slit length $L$ of 42 mm, slit number $N$ of 1, slit width $w$ of 1 mm) BPSCCO plates as functions of frequency $f$, under constant conditions of temperature $T$ of 77.4 K and RF electric output power $P_E$ of the transmitting antenna of 10 dBm. In this figure, the values of RF electric shielding degree $SD_{EN}$ (open squares), $SD_{EH}$ (solid circles), and $SD_{EP}$ (open circles) represent the results for the non-, horizontal-oriented, and perpendicular-oriented (to the ground) slit plates, respectively. It can be seen that the values of $SD_{EN}$, $SD_{EH}$, and $SD_{EP}$ display similar shielding characteristics in the frequency region from 1 MHz to 100 MHz. Furthermore, the values of $SD_{HH}$ increase as the frequency $f$ increases in the region from 100 MHz (32 dB) to 3 GHz (52 dB), while the values of $SD_{HP}$ decrease to an average of 30 dB in this frequency region. Namely, the difference in the values of RF electric shielding degree, $SD_{EH} - SD_{EP}$, of the slit BPSCCO plates indicates the orientation characteristics. These characteristics display a more remarkable effect as the value of $f$ increases. For example, the difference of $SD_{EH} - SD_{EP}$ is approximately 25 dB at 3 GHz.

For the purpose of comparison between orientation characteristics of the electric and magnetic fields, the typical dependence of RF magnetic shielding degree $SD_H$ as functions of frequency $f$ is shown in Fig. 4 [8], for the same BPSCCO plates as shown in Fig. 3, under constant conditions for $T$ of 77.4 K and RF magnetic output power $P_H$ of the transmitting antenna of 10 dBm. In this figure, the values of RF magnetic shielding degree of $SD_{EN}$ (open squares), $SD_{HH}$ (solid diamonds), and $SD_{HP}$ (open diamonds) represent the results for the non-, horizontal-oriented, and perpendicular-oriented slit BPSCCO plates, respectively. In Fig. 4, it can be seen that the values of $SD_{HH}$ are low compared with those of $SD_{HP}$, in the frequency region from 1 MHz to 3 GHz. That is, the orientation characteristics of

![Figure 3](image1.png)

**Figure 3.** The RF electric shielding degree $SD_E$ of the BPSCCO plates as functions of frequency $f$. Here, the open squares ($SD_{EN}$), solid circles ($SD_{EH}$), and open circles ($SD_{EP}$) represent the shielding characteristics for the non-slit, horizontal-oriented slit, and perpendicular-oriented slit plates, respectively.

![Figure 4](image2.png)

**Figure 4.** The RF magnetic shielding degree $SD_H$ of the BPSCCO plates as functions of frequency $f$ [8]. Here, the open squares ($SD_{EN}$), solid diamonds ($SD_{HH}$), and open diamonds ($SD_{HP}$) represent the results of $SD_H$ for the non-slit, horizontal-oriented slit, and perpendicular-oriented slit plates, respectively.
the RF magnetic shielding of the slit BPSCCO plates are opposite to those found in the RF electric shielding. In addition, it can be seen that orientation characteristics in the RF magnetic shielding are obtained over a broader frequency region than those found in the RF electric shielding.

3.2. Dependence of RF electric shielding effects on the slit length \( L \) of the BPSCCO plate

In order to facilitate a systematic investigation of the orientation characteristics for the slit BPSCCO plate (slit number \( N \) of 1, slit width \( w \) of 1 mm), in this research the slit length \( L \) was changed in diapason over the region of 0 mm (non-slit) to 42 mm. Figure 5 shows the characteristics of \( SD_{Eh} \) (solid circles) and \( SD_{Ep} \) (open circles) at 3 GHz as a function of slit length \( L \), under constant conditions for \( T \) of 77.4 K and \( P_e \) of 10 dBm. It is found that values of \( SD_{Eh} \) remain fairly constant at approximately 55 dB in the length region from 0 mm to 42 mm. However, the values of \( SD_{Ep} \) decrease as the slit length \( L \) increases in this region. That is, the differences in the RF electric shielding degree, \( SD_{Eh} - SD_{Ep} \), increase in the region from 14 mm (4 dB) to 42 mm (25 dB). It is found that the orientation characteristics become more remarkable as the values of \( L \) increase.

Similar tendencies for the RF magnetic shielding characteristics for the same plates, as those shown in Fig. 5, were also obtained in the region from 0 mm (\( SD_{Hh}: 54 \) dB, \( SD_{Hp}: 54 \) dB) to 42 mm (\( SD_{Hh}: 20 \) dB, \( SD_{Hp}: 42 \) dB), under same constant conditions as in Fig. 4, as were reported in Ref. [8]. It was also found that the orientation characteristics in RF magnetic shielding as related to the length of the slit are opposite to those found in the RF electric shielding.

3.3. Dependence of RF electric shielding effects on the slit number \( N \) of the BPSCCO plate

Figure 6 displays the distributions of \( SD_e \) for the slit BPSCCO plates (slit length \( L \) of 42 mm, slit width \( w \) of 1 mm) as functions of the slit number \( N \), under the same constant conditions as employed in Fig. 5. In this figure, the values of \( SD_{Eh} \) (solid circles) and \( SD_{Ep} \) (open circles) decrease with increasing values of \( N \) in the region from 1 to 11. It can be seen, however, that the differences in the RF electric shielding degree, \( SD_{Eh} - SD_{Ep} \), remain approximately constant (20 dB) in this slit number region.

From the results reported in Ref. [8], similar tendencies for the RF magnetic shielding characteristics were found for the same plates, and are shown in Fig. 6, in the region of \( N \) from 1 (\( SD_{Hh}: 20 \) dB, \( SD_{Hp}: 42 \) dB) to 11 (\( SD_{Hh}: 3 \) dB, \( SD_{Hp}: 13 \) dB), under the same constant conditions used in Fig. 4. The orientation characteristics in RF magnetic shielding related to the direction of the slit were opposite those found in the RF electric shielding with regard to slit number \( N \).

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Figure 5. Characteristics of \( SD_e \) of the slit BPSCCO plates as functions of slit length \( L \), under the radio frequency of 3 GHz. Here, the solid (\( SD_{Eh} \)) and open (\( SD_{Ep} \)) circles display the results for the horizontal- and perpendicular-oriented slit plates, respectively.

Figure 6. Characteristics of \( SD_e \) of the slit BPSCCO plates as functions of slit number \( N \), under the radio frequency of 3 GHz. Here, the solid (\( SD_{Eh} \)) and open (\( SD_{Ep} \)) circles represent the results for the horizontal- and perpendicular-oriented slit plates, respectively.
3.4. Dependence of RF electric shielding effects on the slit width \( w \) of the BPSCCO plate

Figure 7 displays the dependence of RF electric shielding degree \( SD_E \) of the plate (slit length \( L \) of 42 mm, slit number \( N \) of 1) as functions of the slit width \( w \), under the same constant conditions as found in Fig. 5 and 6. In this figure, \( SD_{EH} \) (solid circles) and \( SD_{EP} \) (open circles) represent the results for the horizontal- and perpendicular-oriented slit BPSCCO plates at 3 GHz, respectively. It is found that both the values of \( SD_{EH} \) and of \( SD_{EP} \) decrease as the slit width \( w \) increases for widths from 1 mm to 11 mm. Furthermore, the slit BPSCCO plates tend to exhibit weaker orientation characteristics when the slit width \( w \) increases in the region from 1 mm (25 dB) to 11 mm (4 dB). Similar tendencies for frequencies in the range from 100 MHz to 3 GHz were obtained for these widths (not shown).

Figure 8 [8] displays the distributions of \( SD_H \) for the same plates as shown in Fig. 7 as functions of the slit width \( w \), under same constant conditions as found in Fig. 4. In this figure, \( SD_{HH} \) (solid diamonds) and \( SD_{HP} \) (open diamonds) represent the results for the horizontal- and perpendicular-oriented slit plates, respectively. It can be seen that the values of \( SD_{HH} \) for the horizontal-oriented slit plate slightly decrease as the slit width \( w \) increases in the region from 1 mm (20 dB) to 11 mm (6 dB). It is also seen that the values of \( SD_{HP} \) for the perpendicular-oriented slit plate remain constant in the width region from 1 mm to 4 mm, and then decrease as the slit width \( w \) increases in the range from 4 mm (42 dB) to 11 mm (26 dB). Furthermore, it is found, with regard to the slit width \( w \), that the orientation characteristics in RF magnetic shielding to the direction of the slit are opposite those found in the RF electric shielding. From the results in Figs. 5−8, the most suitable criteria for better orientation characteristics in RF electric and RF magnetic shields are to fabricate the BPSCCO plate with a longer and narrower slits.

3.5. Rotational characteristics of RF electric shielding effects for the slit BPSCCO plate

In order to clarify the relationship between the RF electromagnetic shielding degree and the rotation angle \( \theta \) of the slit BPSCCO plate, the angle is systematically changed from 0˚ to 180˚ to the ground. For this purpose, a slit BPSCCO plate with a slit length \( L \) of 42 mm, a slit width \( w \) of 1 mm, and slit number \( N \) of 1 is employed, and the results are termed the rotational characteristics. The results were obtained with use of the measuring method as reported in reference [8]. Figure 9 shows the typical rotational characteristics of \( SD_E \) (solid circles) and \( SD_H \) (open diamonds) for the slit BPSCCO plate as functions of the rotating angle \( \theta \) at 3 GHz, under the constant conditions for \( T \) of 77.4 K and the values of \( P_E \) and \( P_H \) of 10 dBm. As can be seen in this figure, it is clear that both the values of \( SD_E \) and \( SD_H \) depend on the rotation angle of the slit. In addition, the rotational characteristics for angles between
180° and 360° obtained similar results as those displayed in Fig. 9.

The results of $SD_E$ and $SD_H$ for measurements similar to those given in Figs. 3–9 for the slit BPSCCO plates displayed no evidence of dependence on the RF output powers $P_E$ and $P_H$ in the region from 0 dBm to 30 dBm (not shown).

![Figure 9. Rotational characteristics of $SD_E$ and $SD_H$ for the slit BPSCCO plates as functions of rotation angle $\theta$, under the radio frequency of 3 GHz. Here, the solid circles (left ordinate) and open diamonds (right ordinate) represent the values of $SD_E$ and $SD_H$, respectively.](image)

### 4. Conclusion

The measured orientation characteristics of RF electric shielding coefficient $SD_E$ of the superconducting slit BPSCCO plate for a plane wave had been unknown until now. The present authors have, therefore, examined and clarified the characteristics of the BPSCCO plate that include the dependencies of $SD_E$ on the slit length, slit width, and slit number. In addition, values of $SD_E$ and $SD_H$ as functions of the rotation angle of the slit BPSCCO plate in the region between 0° and 360° were determined. By comparing the orientation characteristics for electric and magnetic shielding degrees, it was found that in case of the used experimental setup [8], the orientation characteristics for the RF electric shielding of the plates are opposite to those found for the RF magnetic shielding. These results represent important criteria which is fundamental for designing of the practical RF shielding systems that have the spatially orientated shielding characteristics.

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