Cylindrical Cloaking based on Arrangement Density Control of Multilayer Ceramic Capacitors

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Received: July 6, 2021; Accepted: December 19, 2021; Published: January 31, 2022

Abstract. Herein, a cylindrical cloak based on the arrangement density control of multilayer ceramic capacitors (MLCCs) is proposed. The unit cell structure is designed by locating an MLCC between two dielectric substrates. By adjusting the period length of the unit cell structure, the effective permeability of the unit cell can be controlled, thereby enabling the design of the cylindrical cloak. The cylindrical cloak using MLCCs is fabricated and measured in this study. The validity of the simulation results is confirmed by comparing them with the measured results.

Keywords: Cylindrical Cloak, Multilayer Ceramic Capacitor, Arrangement Density Control, Effective Permeability

1. Introduction

In recent years, electromagnetic cloaking technology, which shields the inside of an object from external radio waves by covering an object with a special material, has garnered significant attention [1, 2]. Radio waves incident from an arbitrary direction bend through the cloaking region, avoiding the shielding object and returning to the same trajectory as the incident wave. When observed from outside the cloak, it appears as if no object is present because no reflection or scattering occurs from the shielding object. Therefore, if electromagnetic cloaking can be realized, then it can be applied to communication and military applications, such as mutual coupling reduction between antennas or the concealment of an object on the radar.

Electromagnetic cloaking based on transformation electromagnetics [3-5] can control the propagation of electromagnetic waves via the construction of a medium with appropriate parameters in space, based on the medium interpretation using coordinate transformation.
However, the medium constants used to construct cloaking must be heterogeneous or anisotropy; as such, electromagnetic cloaking is difficult to achieve using natural materials. As a solution, artificial materials known as metamaterials with unique properties that are not observed in nature have been used to realize cloaks. In a previous study, a cylindrical cloak composed of split ring resonators (SRR) was investigated [6]. To achieve the desired effective permeability distribution, the structural parameters of the SRRs were adjusted, and the SRRs were placed in 10 layers around the shielding object to create an anisotropic medium [6]. However, because the unit cell size was large, the cylindrical cloak structure became thicker and hence could not be loaded onto the narrow objects. Therefore, the unit cell must be miniaturized to design a thin cylindrical cloak structure.

The possibility of synthesizing metamaterials using multilayer ceramic capacitors (MLCCs) has been investigated [7, 8]. It has been confirmed that MLCCs can achieve a negative effective permeability near the resonant frequency when periodically arranged. When the magnetic flux penetrates between the inner electrodes of the MLCC, the MLCC resonates and a loop-shaped current is generated. It has been confirmed that the operating principle of the MLCC is the same as that of the SRR. Moreover, because the MLCC is extremely small, the unit cell of the metamaterials can be miniaturized. Therefore, a thin cylindrical cloak using MLCCs has been proposed [9]. By adjusting the internal structural parameters of the MLCC, the effective permeability of the unit cell can be controlled, and it has been confirmed that the desired effective permeability distribution for designing 10 layers of the thin cylindrical cloak can be obtained. However, to use this method, 10 types of MLCCs with different internal structures must be prepared. Therefore, another method for controlling the effective permeability of the unit cell is required without changing the internal structural parameters of the MLCC. Accordingly, a thin cylindrical cloak that controls the arrangement density of MLCCs has been proposed [10]. By adjusting the period length of the unit cell structure, it has been confirmed that the effective permeability can be controlled, and the thin cylindrical cloak can be designed with only one type of MLCC. However, the results presented in [10] are only simulation results, and the effect of the cylindrical cloak using MLCCs has not been verified via measurements.

Herein, a cylindrical cloak based on the arrangement density control of MLCCs is proposed. The MLCC was modeled as a basic structure, and the unit cell structure was designed by locating an MLCC between two dielectric substrates. By adjusting the period length of the unit cell structure, the effective permeability of the unit cell can be controlled, thereby confirming that the cylindrical cloak can be designed. A cylindrical cloak was fabricated and measured using MLCCs. The validity of the simulation results was confirmed by comparing them with measured results.

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2. Cylindrical cloak based on arrangement density control of MLCCs

2.1. Proposed cylindrical cloak and unit cell structure

The configuration of the cylindrical cloak based on the arrangement density control of the MLCCs is shown in Fig. 1. In the cylindrical cloak structure, MLCCs are periodically arranged in the circumferential direction on a dielectric substrate, and they are segmented into 10 layers. The sizes of the proposed cylindrical cloak were the same as that of the cylindrical cloak in [5], and the inner and outer radii of the cylindrical cloak structure were $R_1 = 27.1$ mm, and $R_2 = 58.9$ mm, respectively. Additionally, the cylindrical cloak in this study was illuminated by a normal incident plane wave with an electric field polarized along the $z$-axis (TM$_z$ cloak).

![Figure 1: Configuration of the cylindrical cloak structure based on the arrangement density control of the MLCCs](image)

Figure 2 shows the proposed unit cell structure. The unit cell structure measured $p_x$ [mm] (period length) $\times$ 3.18 mm (width) $\times$ 1.92 mm (height). The period length $p_x$ was the inner radius of the unit cell. The MLCC was located between two dielectric substrates with a relative permittivity $\varepsilon_r = 3.4$ and tangent loss $\tan\delta = 0.0015$. The thickness of the dielectric substrate was 0.5 mm. In addition, as shown in Fig. 2(b), the spacing between the MLCC and upper dielectric substrate was 0.05 mm. Figure 3 shows the structure of the MLCC. The MLCC was modeled as a basic structure comprising a dielectric ceramic, plating, as well as inner and outer electrodes. The external dimensions of the MLCC were 1.27 mm $\times$ 0.87 mm $\times$ 2.02 mm. The relative permittivity of the internal dielectric ceramic material was $\varepsilon_{in} = 27$, and the length of the plating is 0.51 mm. Two pairs of inner electrodes were modeled and arranged near the upper and lower sections of the dielectric ceramic material of the MLCC. The length of each
inner electrodes was 1.16 mm, and the distance between the two neighboring inner electrodes was 0.1 mm, as shown in Fig. 3(b). The resonant frequency of the MLCC was 8.1 GHz, and the capacitance was 3.6 pF.

2.2. Effective permeability characteristics of unit cell structure

The effective permeability of the unit cell structure was extracted from the simulated S-parameters [11]. The ANSYS high-frequency structure simulator version 19 with the finite element method was employed for the simulation. Figure 4 shows the effective permeability characteristics of the unit cell structure when \( p_x \) was varied from 2.5 to 3.5 mm. As shown in Fig. 4, when \( p_x \) decreased, the resonant frequency of the unit cell structure remained almost unchanged, and the band in which the effective permeability was negative widened. Moreover, as shown in the enlarged view of Fig. 4, the effective permeability of the unit cell structure can be finely controlled by adjusting the period length \( p_x \).
2.3. Designed results

As shown in Fig. 1, when the incident electric field is parallel to the z-axis of the cylindrical cloak structure, the effective permittivity and permeability tensors of each layer can be simplified as follows [5]:

\[
\mu_r = \left(\frac{r - R_1}{r}\right)^2, \quad \mu_\theta = 1, \quad \varepsilon_r = \left(\frac{R_2}{R_2 - R_1}\right)^2
\]

(1)

Here, \(R_1\) and \(R_2\) are the inner and outer radii of the cylindrical cloak structure, respectively, and \(r\) is the radial coordinate with \(R_1 < r < R_2\). In each layer, because \(\mu_r\) varies with \(r\), it is difficult to manufacture a cylindrical cloak structure that can change the effective permeability of each layer continuously. Therefore, the distribution of the \(\mu_r\) was approximated stepwise. When the cylindrical cloak structure was segmented into 10 layers, the \(\mu_r\) in each layer can be designed by adjusting the period length of the unit cell. The period length \(p_x\) was calculated so that the number of unit cells in each layer was an integer. The effective permittivity of the unit cell was extracted using the value of each \(p_x\), and the period length \(p_x\) when the effective permittivity becomes the closest value to the theoretical value was determined. The designed results for 10 layers of the proposed cylindrical cloak at 8.25 GHz are presented in Table 1. As shown in Table 1, the designed values of the effective permittivity and permeability tensors in
each layer agreed relatively well with the theoretical values obtained by stepwise approximation of Expression (1) when the cylindrical cloak was segmented by 10 layers.

Table 1: Design results for 10 layers of the proposed cylindrical cloak at 8.25 GHz

| Layer No. | $p_x$ [mm] | The number of MLCC | Theoretical values $\varepsilon_z$ | $\mu_r$ | Design values $\varepsilon_z$ | $\mu_r$ |
|-----------|------------|--------------------|-----------------------------------|-------|-----------------------------|-------|
| 1         | 2.746      | 62                 | 3.431 0.003                       | 3.589 0.004 |
| 2         | 2.839      | 67                 | 3.431 0.022                       | 3.528 0.042 |
| 3         | 2.919      | 72                 | 3.431 0.051                       | 3.516 0.053 |
| 4         | 3.029      | 76                 | 3.431 0.085                       | 3.466 0.088 |
| 5         | 3.167      | 79                 | 3.431 0.119                       | 3.417 0.132 |
| 6         | 3.335      | 81                 | 3.431 0.154                       | 3.361 0.153 |
| 7         | 3.413      | 85                 | 3.431 0.187                       | 3.309 0.193 |
| 8         | 3.524      | 88                 | 3.431 0.219                       | 3.254 0.220 |
| 9         | 3.549      | 90                 | 3.431 0.249                       | 3.252 0.253 |
| 10        | 3.685      | 95                 | 3.431 0.278                       | 3.243 0.277 |

2.4. Analysis model and simulation results

Because the finite structure of the cylindrical cloak could not be analyzed, as shown in Fig. 1, a two-dimensional (2D) analysis model was applied to reduce the computational cost, and COMSOL Multiphysics 5.6 was employed to perform the simulation. Figure 5 shows the 2D analysis model. The model was a structure comprising a perfect electric conductor (PEC) cylinder and a cylindrical cloak. This model did not include a specific model of the MLCC. The inner and outer radii were $R_1 = 27.1$ mm, $R_2 = 58.9$ mm, respectively, and the cylindrical cloak was segmented into 10 layers. The plane wave was incident from negative x-axis direction.

The designed results shown in Table 1 were set for each layer of the cylindrical cloak, and the electric field distribution was simulated. Figure 6 shows the simulated electric field distributions of the PEC cylinder only, and that of the proposed cylindrical cloak at 8.25 GHz. In the former case, the reflection and scattering were intense, and the electric field intensity behind the PEC cylinder weakened. However, when a cylindrical cloak was used, the reflection and scattering became less intense, confirming that the plane wave circumvented the PEC cylinder in the cloak region.

In addition, for a quantitative comparison, a one-dimensional (1D) electric field value on
the center line of the cylindrical cloak was simulated. Figure 7 shows a comparison of the 1D electric field values of the free space, PEC cylinder and cylindrical cloak. The region from \( x = -27.1 \) mm to \( x = 27.1 \) mm was the region of the PEC cylinder; therefore, the values of the 1D electric field could not be calculated and the line of the 1D electric field was interrupted in this region. On the reflection side, the electric field strength in the case of the PEC cylinder was higher than that of the free space, whereas it is lower on the transmission side. However, when the cylindrical cloak was used, the electric field strength of the cylindrical cloak was similar to that of the free space. Therefore, it can be confirmed that the reflection and scattering reduced, which is consistent with the simulated electric field distribution shown in Fig. 6.

Figure 5: 2D analysis model
Figure 6: Simulated electric field distributions at 8.25 GHz

(a) PEC cylinder

(b) Cylindrical cloak

Figure 7: Comparison of 1D electric field values of the free space, PEC cylinder and cylindrical cloak
3. Prototype structure of cylindrical cloak and measurement results

3.1. Prototype structure

The cylindrical cloak based on the arrangement density control of MLCCs was fabricated to yield the designed results discussed in Section 2. MLCCs obtained from Murata Manufacturing Co., Ltd. (model number: GQM2195C2E3R6) were employed. Each MLCC had a capacitance value of 3.6 pF. The MLCC was installed on a dielectric substrate with a thickness of 0.5 mm, relative permittivity of 3.4, and dielectric loss tangent of 0.0015. Figure 8 shows a photograph of the prototype cylindrical cloak. The cylindrical cloak surrounded a metal cylinder of radius 27.1 mm, and the outer radius and cylindrical cloak thickness were 58.9 and 8.5 mm, respectively. A four-layer cylindrical cloak structure was fabricated by stacking four pairs of MLCC-mounted and unclad substrates in the z-axis direction. In addition, the MLCC was mounted using the reflow soldering method, and the number of MLCCs installed on a single substrate was 795.

![Prototype structure of the cylindrical cloak](image)

(a) General view

(b) Cylindrical cloak structure without the upper unclad dielectric substrate

Figure 8: Prototype structure of the cylindrical cloak

3.2. Measurement setup

A 2D electromagnetic field mapping measurement system was fabricated to measure the electric field distribution of the cylindrical cloak. Figure 9 shows the electromagnetic field mapping measurement device. The measurement equipment included a vector network analyzer (VNA) and an amplifier, and a parallel plate waveguide was constructed using two metal plates on the transmitting and receiving sides as well as a waveguide adapter. The metal plate on the
transmitting side was fixed, and a radio wave absorber and waveguide adapter were attached to it. The metal plate on the receiving side was moved using an XY scanner. In addition, a probe was connected to the center of the metal plate on the receiving side.

Figure 10 shows an overview of the measurement systems. Port 1 of the VNA was connected to a waveguide adapter on the transmitting side, which irradiated the sample through a waveguide with a tapered absorber. Next, the XY scanner on the receiving side scanned horizontally and vertically, and the data measured at each position were transferred from the probe to port 2 of the VNA. The measured results were displayed using the LabVIEW measurement program.

![Figure 9: 2D electromagnetic field mapping measurement equipment](image)

![Figure 10: Overview of measurement system](image)
3.3. Measurement results

First, the measurement was performed only for the case involving the metal cylinder. The measurement frequency range was from 8-12.5 GHz in the X-band, and the measurement frequency interval was 11.25 MHz. The width of the waveguide was 160 mm, and the measurement ranges were 250 and 300 mm in the horizontal and vertical directions in 1 mm intervals, respectively. A metal cylinder was attached to the metal plate of the transmitting side using a conductive double-sided tape. Figure 11 shows the measured real part of the electric field distributions of the metal cylinder at 8.25, 8.56, and 8.7 GHz. The plane wave was incident from the \(-z\) direction, and it was confirmed that the reflection and scattering were intense, whereas the electric field strength behind the metal cylinder was weak. The measured electric field of the metal cylinder at 8.25 GHz agreed relatively well with the simulated results shown in Fig. 6(a). Figure 12 shows the measured phase distributions of the metal cylinder at 8.25, 8.56, and 8.7 GHz. This confirms that the phases of the front and back of the metal cylinder were disrupted, which is consistent with the measured real part of the electric field.

![Image of measured real part of the electric field distributions](image1)

Figure 11: Measured real part of the electric field distributions of the metal cylinder

![Image of measured phase distributions](image2)

Figure 12: Measured phase distributions of the metal cylinder

Figure 13 shows the measured real part of the electric field distributions of the cylindrical cloak at 8.25, 8.56, and 8.7 GHz. At 8.25 and 8.7 GHz, the reflection and scattering were intense,
and the electric field distribution behind the cylindrical cloak was disrupted. By contrast, the reflection and scattering decreased at 8.56 GHz, and the plane wave circumvented the metal cylinder. Figure 14 shows the measured phase distributions of the cylindrical cloak at 8.25, 8.56, and 8.7 GHz. At 8.25 GHz and 8.7 GHz, the phase behind the cylindrical cloak was disrupted; however, it was almost uniform at 8.56 GHz. In addition, it confirms that the phase of the central section behind the cylindrical cloak at 8.56 GHz was out of phase owing to the weak electric field strength. Accordingly, the effect of the cylindrical cloak based on the arrangement density control of MLCCs was confirmed.

![Figure 13: Measured real part of the electric field distributions of the cylindrical cloak](image1)

![Figure 14: Measured phase distributions of the cylindrical cloak](image2)

However, the operating frequency of the fabricated cylindrical cloak was higher than the design frequency, and it could be considered that this was caused owing to the variation in the MLCCs. The capacitance of the MLCC used for fabrication had an allowable error of ±0.1 pF; therefore, the resonant frequency due to the simulation results considering the size of the fabricated cylindrical cloak might not agree well with the measured frequency. In addition, by adjusting the length of the inner electrodes of the MLCC structure, the capacitance of the MLCC could be controlled. When the inner electrodes length was 1.15 mm, the capacitance of the MLCC was 3.5 pF, and the resonant frequency of the MLCC became 8.25 GHz. When the
inner electrodes length was 1.17 mm, the capacitance of the MLCC was 3.7 pF, and the resonant frequency of the MLCC became 7.96 GHz. Therefore, it was considered that the variation of the MLCC could make the resonant frequency of the MLCC change. And, it could be considered that the prototype cylindrical cloak had many MLCCs with short internal electrodes. Furthermore, because of the variation in the MLCCs, the frequency band of the negative effective permeability of each layer widened [12], and it can be assumed that the desired values of the effective permeability obtained via the cylindrical cloak design appeared on the high frequency side.

4. Effect of cylindrical cloak loss

4.1. Electric field distribution

As presented in section 3.3, the electric field strength behind the cylindrical cloak weakened; therefore, in this section, the effect of the cylindrical cloak loss is analyzed.

Figure 15 shows the simulated electric field distribution of the cylindrical cloak with the addition of electric and magnetic loss tangents at 8.25 GHz. As shown in Fig. 15, when the loss tangent was considered, the electric field strength behind the cylindrical cloak weakened, and the electric field strength decreased when the loss tangent increased. In addition, when the loss tangent was set to 0.1, the simulated electric field distribution of the cylindrical cloak had almost same phenomenon as the measured electric field distribution in Fig. 13. However, the incident wave in measurement was like a spherical wave due to the placement of the radio wave absorbers which consist of a waveguide; therefore, it could seen that the electric field distributions in Fig. 13 and Fig. 15 were not agreement well.

(a) \[\tan \delta = 0\] (b) \[\tan \delta = 0.05\] (c) \[\tan \delta = 0.1\]

Figure 15: Simulated electric field distribution of the cylindrical cloak with the addition of loss tangent at 8.25 GHz.
4.2. Confirmation of cylindrical cloak loss tangent via 1D electric field strength

To quantitatively confirm the loss tangent of the fabricated cylindrical cloak, the simulated results of the 1D electric field strength on the center line of the cylindrical cloak were compared with the measured results. The simulated and measured results of the 1D electric field strength were normalized to the maximum value.

Figure 16 shows a comparison between the simulated and measured results of the 1D electric field strength of the metal cylinder. On the reflection side, the electric field strength increased when the plane wave approached the PEC cylinder, whereas the electric field strength behind the PEC cylinder decreased. Moreover, on the transmission side, the electric field strength increased when the plane wave propagated away from the PEC cylinder. Therefore, this confirms that the simulated results agreed relatively well with the measured results, although the phases of the simulated and measured results deviated slightly.

Figure 17 shows a comparison between the simulated and measured results of the 1D electric field strength of the cylindrical cloak. In the simulation results, the electric field strength on the reflection side decreased when the plane wave entered the cylindrical cloak region. However, it increased in measured results. Hence, it can be assumed that the reflections occurred in the cylindrical cloak region. On the transmission side, the measured electric field strength was weaker than that of the lossless cylindrical cloak. Since the electric field strength on the transmission side became weak when the loss of the cylindrical cloak was considered, a loss tangent of 0.1 was determined in order to match the simulated electric field strength on the transmission side with the measured results. When the loss tangent of 0.1 was considered, the simulated electric field strength on the transmission side weakened, which is consistent with the measured results. Therefore, it can be confirmed that the loss tangent of the fabricated cylindrical cloak was approximately 0.1. However, in the measured results, the phase of the 1D electric field in the transmission side was inverted compared to the simulated results. The reason for the phase shift could be estimated as to the difference between the simulation model and prototype structure for measurement. The simulation model was an ideal isotropic model in which the effective permittivity and permeability of each layer were set, and it did not include a specific model of the MLCC. However, in the measurement structure, the MLCCs were arranged discretely. Therefore, it could be considered that the phase shift on the transmission side occurs due to the loss of the MLCCs.
5. Conclusion

In this paper, a cylindrical cloak based on the arrangement density control of MLCCs was proposed. The MLCC was modeled as a basic structure, and the unit cell structure was designed by locating the MLCC between two dielectric substrates. By adjusting the period length of the unit cell structure, the effective permeability of the unit cell was controlled successfully, and it was confirmed that the cylindrical cloak can be designed by controlling the arrangement density of the MLCCs. Subsequently, a cylindrical cloak using MLCCs was fabricated and measured. The effect of the cylindrical cloak was confirmed at 8.56 GHz, and the simulation results
were validated. In addition, the operating frequency of the cylindrical cloak was higher with
the designed frequency, which was assumed to be due to the variation in the MLCCs. Furthermore,
the electric field strength behind the cylindrical cloak weakened, which was speculated
to be due to the loss tangent of the cylindrical cloak. By comparing the simulated and measured
results of the 1D electric field strength on the center line of the cylindrical cloak, it was con-
firmed that the fabricated cylindrical cloak had a loss tangent of approximately 0.1. In this
paper, it was demonstrated that the cylindrical cloak based on the arrangement density control
of MLCCs could be designed. In future work, by using proposed structure, the miniaturized
cylindrical cloak will be designed by reducing of the layers, or by using an MLCC with a small
size compared with the proposed MLCC in this study for miniaturizing the unit cell structure
of the cylindrical cloak.

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