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Method of measuring the amounts of electromagnetic radiation absorbed and controlled by metamaterials in anechoic chamber

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ABSTRACT

This study has proposed a method of measuring the characteristics of electromagnetic (EM)-wave absorption and diffraction using MM absorbers (MAs). Metamaterials (MMs) can absorb or affect EM waves towards desired directions. There are a number of ongoing studies on the development of MAs for EM waves. However, as of yet no method of quantitatively evaluating the EM waves absorbed by MM has been clearly defined. It has been explained that the EM characteristics caused by MMs can be explained using Poyntings vector theorem. However, it is necessary to develop a practical alternative to the use of this theorem, because the theoretical evaluations have limitations due to the ideal properties of an antenna for measurement of EM waves and the size of MMs. Thus, this study has suggested that factors to be considered in measuring the characteristics of EM waves absorbed by MMs include distance between MM and antenna, performance characteristics of antenna, conditions of test field, measuring instrument, and measuring system. With a measurement system established, the MMs EM characteristics, which are represented by the amounts of EM waves absorbed and controlled by MMs, can be measured by generating EM waves from the antenna and comparing the differences between when there is a MM absorber and when there is no MM absorber at a location which is a certain distance (far-field) away from the source of the EM waves. This study has shown the amounts of EM waves absorbed by and controlled by MMs by using antennas with 2.4 and 4 GHz bandwidths.

1. Introduction

Eletromagnetic (EM) waves, when radiated into space, are characterized by attenuation, reflection, and diffraction as they propagate through the space. EM waves are characterized by free-space attenuation, as the electrical field and the magnetic field intersect each other at a right angle. In addition, attenuation or absorption, in which the magnitude of a signal diminishes, occurs when the EM waves traveling in a straight line come into contact with certain materials. The EM can be reflected in the reverse direction and diffracted around the material. In order to measure the various properties of the EM-wave absorption, transmission and reflection, the three-dimensional measuring method was already proposed for the spatial radio channel [1]. Recently, the three-dimensional EM-wave transmission patterns was suggested according to the measurement by the angle and the distance of receiving antenna [2]. To increase the accuracy, in addition, the EM field was measured in the anechoic chamber [3–5].

Metamaterials (MMs) are smart materials that are capable of artificially controlling the attenuation, reflection, and diffraction of EM waves, such as negative refractive index [6], extraordinary optical transmission [7], electromagnetically-induced transparency [8,9], inverse Dopppler effect [10], perfect lens [11], EM-wave clocking [12], and perfect MM absorber [13–19]. The amount of the EM waves that are absorbed and the manner in which the EM waves are controlled is essential in determining the properties and the qualities of MMs. Currently, there are many ongoing studies on how the characteristics of EM waves can be changed using MMs [19–24]. However, there has been no clearly defined method that allows us to evaluate how much of EM waves are absorbed and controlled by MMs. In order to obtain the absorption of MMs, in genernal, the scattering parameters of the incident beam and the reflected beam were measured using network analyzer [25,24,26].

In this study, we have established a measuring system in order to evaluate the characteristics of EM waves that are affected by

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MMs. In addition, the changes in the characteristics of EM waves have been investigated by generating EM waves from 2.4 and 4 GHz antennas and comparing the amounts of EM waves absorbed or controlled by MMs, depending on the existence of MMs in far-field conditions. In order to test the changes in the characteristics of EM waves caused by MMs, we have selected horn antennas, which have narrow beam width and low back lobes at the investigated frequency, and designed a metal-patterned, ring-shaped MM which would cause absorption to occur at 2.4 and 4 GHz. The fundamental concepts and the issues of the measurements, the details of MM EM characteristic system, and the measuring procedures are further discussed in Sections 2–4, respectively, and the measurement results are discussed in Section 5. Finally, this study aims to propose a test method that would allow the investigation of the changes of EM waves that determine the property and the quality of MM through actual measurement.

2. Fundamental concepts of measuring characteristics of EM waves in MMs

2.1. Characteristics and measurements of EM waves

The total power of radiated EM waves that are generated into space can be calculated by applying divergence theorem [27]. Formula (1) below shows the total power at the source of an EM wave, and Fig. 1 explains the basic concepts of measuring the total power of a radiated EM wave.

$$\text{Total power of radiated EM wave (EMR)} = (\mathbf{E}\times\mathbf{H})ds + (\text{Free} - \text{space attenuation}). \quad (1)$$

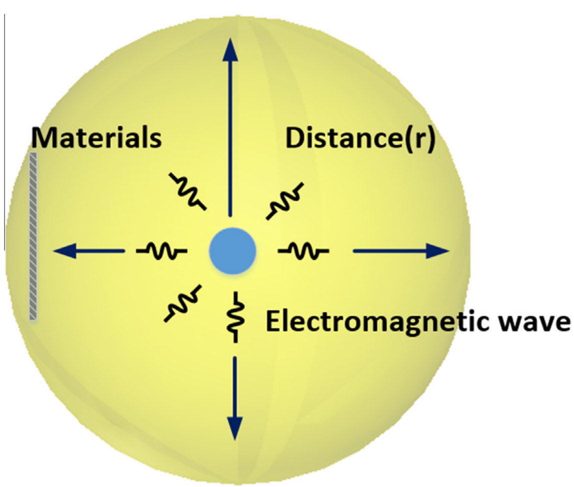

Fig. 1. Basic concept of measuring total power of radiated EM wave.

When EM waves are generated from the center as shown in Fig. 1, the total power of a radiated EM wave can be calculated by aggregating the electromagnetic waves received by scanning the surface of the sphere that is distance r away from the source. Unless there is a lossless condition between the source and the point that is distance r away, attenuation needs to be taken into account, because free-space path loss is inevitable.

2.2. Basic concepts and issues of measuring characteristics of EM waves

If a certain material is placed in the middle of a sphere under a condition like Fig. 1, the measured values can vary depending on the EM characteristics of the material. The EM characteristics (attenuation, absorption, reflection, and diffraction) of the material can be defined by comparing the values measured in a free space to the values measured with the material in place. The amounts of EM waves that are attenuated or absorbed by the material can be calculated by comparing the aggregate sum of the volume of the sphere under free-space condition, and with the material placed within the sphere. In addition, the reflected and diffracted values of EM waves can be measured by comparing the magnitudes of EM radiations along the volume of the sphere.

MMs can cause EM-propagation characteristics, which are absorption and reflection, diffraction and attenuation, by absorbing or controlling the EM waves. Fig. 2 explains the concept of measuring absorption control of EM waves. The amount of EM absorption can be measured by comparing the EM waves radiated from an antenna in a free space with MMs and in a free space without MMs.

The measurement procedures for MMs and the method of measuring the absorption control are as follows.

(1) EM waves are generated in a free space by using an antenna as shown in Fig. 2(a), and are measured by scanning the surface of the sphere.
(2) An antenna is installed to generate EM waves into a free space, and a MM is placed between two antennas as shown in Fig. 2(b), and the EM waves are measured by scanning the surface of the sphere.
(3) Record the measured value of EM waves scanned on each surface in (1).
(4) Record together the measured value of EM waves scanned on each surface in (2).
(5) Calculate the amount by using the following equation: Amount of EM radiation absorbed by the MM = (3) - (4).
(6) The characteristics of EM radiation controlled by the MM can be measured by comparing the amount of EM radiation measured at each point by scanning the surface of the sphere in steps (1) and (2).

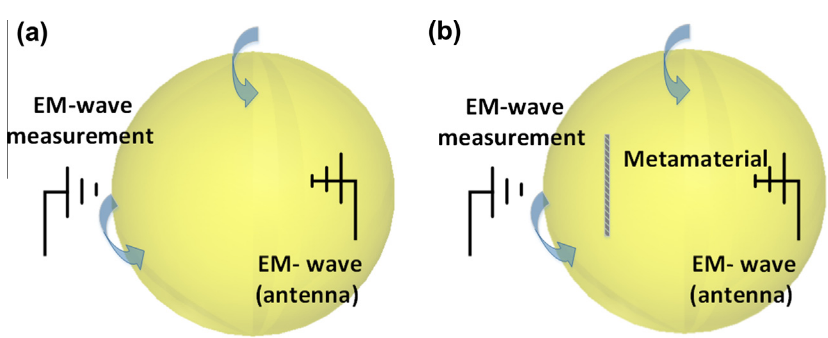

Fig. 2. Basic concept of measuring amount of EM absorption. (a) Free-space measurement and (b) metamaterial measurement.