Infrared Invisibility Cloak Using Rolled Metamaterial Film

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Abstract: We propose and demonstrate a method of making an infrared (~60 THz) invisibility cloaking device by simply rolling a metamaterial film around an object that we want to hide.
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1. Approach to invisibility cloak using metamaterial films

One of recently featured topics in applied optics is optical camouflage (invisibility cloak) realized by manipulating the spatial distribution of permeability and permittivity around an object, using metamaterials. To achieve the optical camouflage, it is needed to make a photonic metamaterial, a three-dimensional array of minute electromagnetic elements whose dimension and array pitch are smaller than the wavelength of light. To make metamaterials for use invisible and infrared light, a few methods have been proposed; leading examples are microfabrication using focused ion beam technology [1] and that using two-photon absorption process [2]. However, a simpler method is needed to develop wide applications of optical camouflage devices using metamaterials.

For this purpose, we have developed a photonic metamaterial consisting of a two-dimensional minute metal-resonator array embedded in a flexible, transparent polymer film [3]. A three-dimensional metamaterial can be made simply by stacking the films. In this paper, we propose and demonstrate a method of making a cloaking device simply by rolling this metamaterial film around an object that we want to hide.

2. Concept and design theory of cloaking device formed with metamaterial film

Figure 1(a) illustrates the concept of our cloaking device. The cloaking region (or object to be hidden) is cylindrical. A metamaterial film is rolled around the cylindrical region. If the permeability μ and permittivity ε of the film are changed appropriately along the rolling direction x (see Fig. 1(b)), then a spatial distribution of μ and ε needed for cloaking can be achieved around the cylindrical region. The appropriate μ-ε profile of the film in the x-direction can be calculated as follows. First, the spatial μ-ε profile around the cylindrical region needed for cloaking is calculated with the aid of transformation optics. Then, the μ-ε profile of the film can be calculated using transformation from the spiral coordinate to the Cartesian coordinate.

In this paper, we calculated the μ-ε profile required for the metamaterial film, assuming 60 THz incident light with polarization shown in Fig. 1(a), a cylindrical cloaking region with 100 μm diameter, and a film thickness of 4 μm. Figure 2(a) shows the calculated μ-ε profile. In the case of assumed polarization of light, the required value of ε is constant and independent of x. The value of μ depends on the number of film rolling. In this example, the rolling number were set to 25 such that ε is almost the same as that of film polymer we used for device fabrication (therefore, it is only necessary to change only μ using metamaterial). Using this μ-ε profile, we calculated electromagnetic field distribution inside and outside the rolled metamaterial film. Figure 2(b) shows the result. Light is deflected around the cloaking region, causing an object in the region to be invisible.

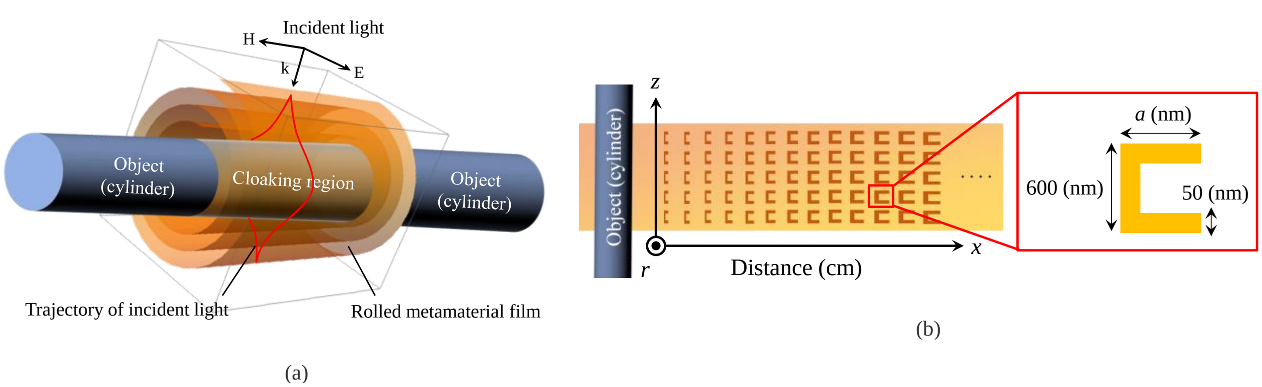

Fig. 1 (a) Metamaterial film rolled around cylinder (rolled part is made transparent); (b) metamaterial film before rolling (having metal resonators whose dimension depends on distance x).

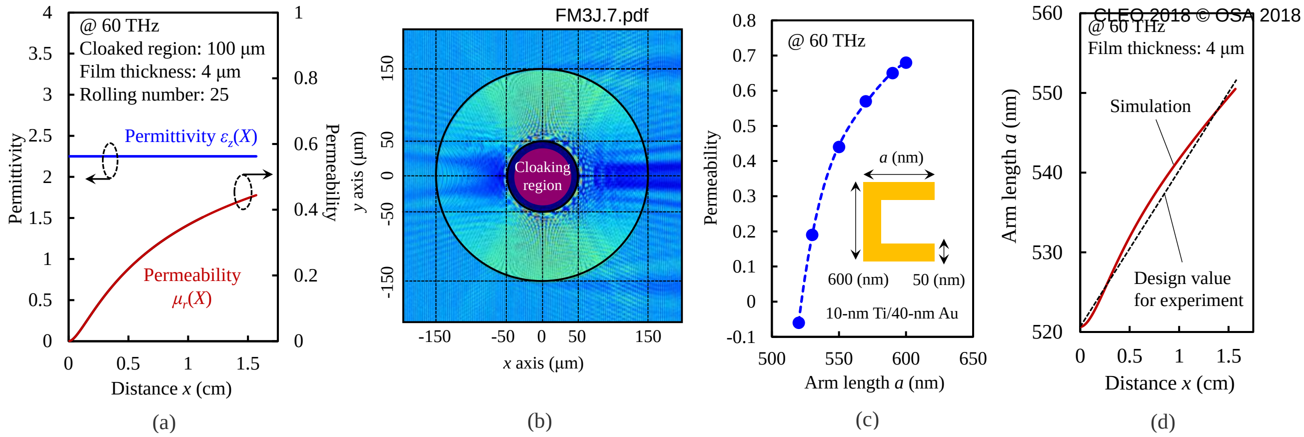

Fig. 2 (a) Calculated μ-ε profile of film needed for cloaking; (b) electromagnetic field simulation around rolled film; (c) resonator dimension versus μ; (d) required resonator dimension as a function of distance x.

To achieve the profile of μ shown in Fig. 2(a), we embedded, in the film, an array of metal ring resonators whose dimension is changed with distance x. Figure 2(c) shows the calculated value of μ as a function of the arm length a of the resonator. The required arm length a is nearly a linear function of x as shown in Fig. 2(d).

3. Metamaterial film fabrication, device formation, and cloaking operation

Figure 3(a) shows a photograph of the metamaterial film we used in this study (for embedded metamaterial dimensions, see Fig. 2(d)). Detailed information on the fabrication can be found in ref. [3]. After preparing the film, it was sandwiched between two flat glass plates together with a SUS rod (100 µm diameter) and rolled around the SUS rod by sliding the glass plates. Figure 3(b) shows the completed device.

We confirmed by experiment the cloaking operation of the device. As shown in Fig. 3(c), the device was placed just above a glass substrate on which a metal pattern (the left end of Fig. 3(d)) was formed. After that, imaging was performed using Fourier transform infrared spectroscopy (IRTracer-100 and AIM-9000, Shimadzu Corp.); the polarization of incident light was set as shown in Fig. 1(a). The results of imaging are shown in Fig. 3(d). At a frequency of 63 THz, we were able to observe the metal pattern under the SUS rod. This shows that the roll of the metamaterial film successfully acts as an invisibility cloak, and light is guided so as not to hit the SUS rod to make the rod seem invisible. (Imaging was disturbed at 58.5 THz because of infrared absorption of the glass substrate, but this has nothing to do with device operation). This cloaking method is a practical technology that can be applied to the cloaking of relatively large objects in not only infrared but also visible light band.

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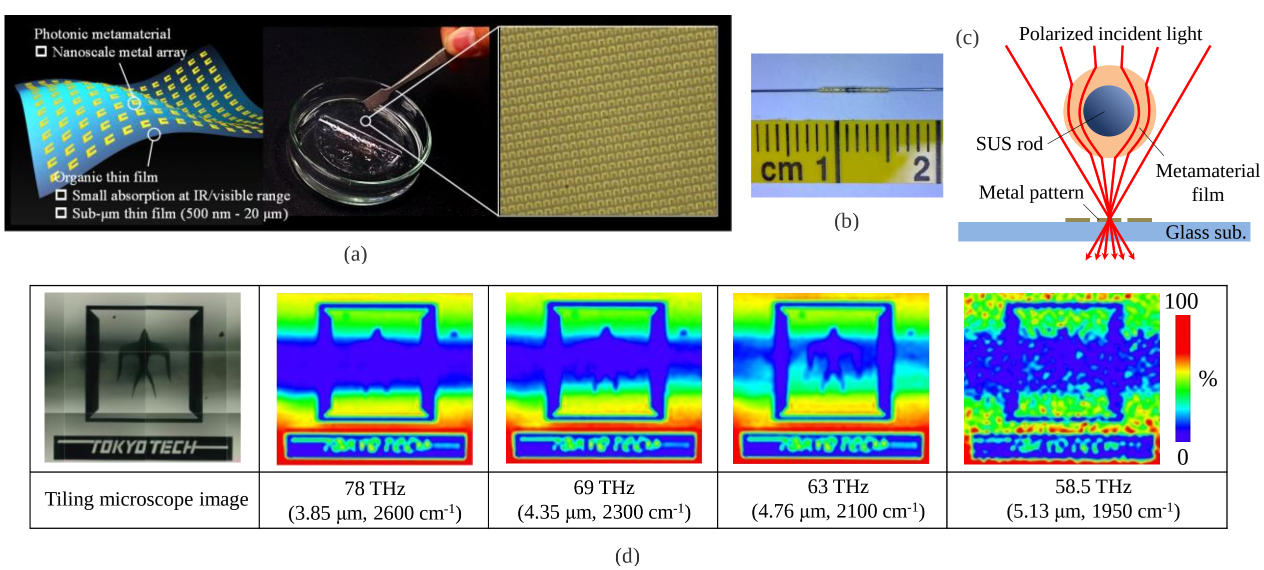

Fig. 3 (a) Fabricated metamaterial film (floating on water surface); (b) photograph of fabricated device; (c) measurement using Fourier transform infrared spectroscopy (FTIR); (d) results of FTIR imaging for various frequencies.