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Experimental realization of breaking diffraction limit by planar negative-index metamaterials in free space

J.-S. Lih [1], Y.-S. Wang [1], M.-C. Lu [1], Y.-C. Huang [2], K.-H. Chen [2], J.-L. Chern [2,3] and L.-E. Li [4]

[1] *Department of Physics, National Cheng Kung University - Tainan 701, Taiwan*
[2] *Department of Photonics & Institute of Electro-Optical Engineering National Chiao Tung University - Hsinchu 300, Taiwan*
[3] *Microelectronics and Information System Research Center National Chiao Tung University - Hsinchu 300, Taiwan*
[4] *Agilent Technol Inc - Jhongli, Taoyuan 320, Taiwan*

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Abstract. – The sharpness of the image formed by a conventional lens is always limited by the wavelength of light. Recently, Pendry proposed a superlens, with a negative refractive index, such that the resolution is not limited by wavelength. Herein, we report direct experimental evidence of Pendry's superlens breaking the diffraction limit, in the microwave range of the X band (8–12 GHz), with a periodic array of split ring resonators and continuous wires; *i.e.* a meta-material with negative index of refraction.

In 2000, Pendry proposed a superlens, which he predicted could lead to a perfect lens, with a resolution not limited by wavelength, and a numerical demonstration of a resolved scale of ~ 80 nm, using an optimized wavelength of 356.3 nm [1]. One of the key factors in achieving this type of perfect lens is the unconventional negative refractive index material, which was explored by Veselago about three decades ago [2]. Veselago pointed out that materials with simultaneously negative permittivity and permeability (*i.e.*, left-handed material; LHM) have unusual reversed electromagnetic-wave propagation phenomena, as compared to a common medium (right-handed material; RHM). In 2001, using a left-handed metamaterial, formed by a periodic array of split ring resonators (SRRs) and continuous wires, Shelby, Smith and Schultz experimentally established the reversion of Snell's law [3], in the microwave range. Further experimental results showed that SRRs also exhibit resonance around 10.6 μm, implying negative permeability in the far-infrared region [4]. Following the basic framework of wire SRRs, different patterns with deformed SRRs were verified, to simultaneously exhibit the negative values of effective permeability and permittivity [5–8]. Such metamaterials exhibit properties not observed in naturally occurring materials and are expected to have a variety of

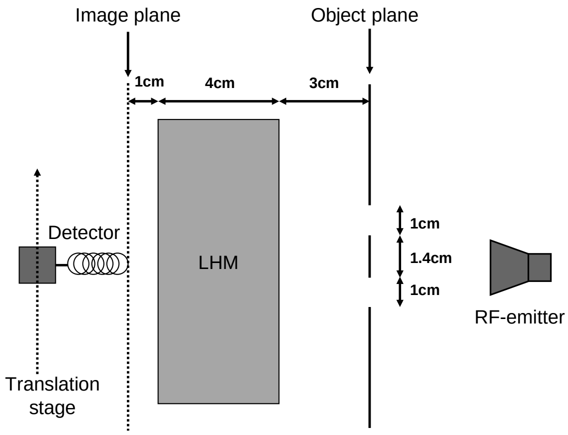

Fig. 1 – Schematic diagram of the experimental setup.

practical applications, such as beam steerers, modulators and band-pass filters. Recently, there have been extensive arguments on the realization and the foundation of the superlens [9–14]. Pendry's superlens proposal, using metamaterials, examined numerically by several research studies was shown to be imperfect, due to the surface mode [15] and the retardation effect of LHM, with losses and dissipation [16, 17]. More recent numerical analyses of the imaging quality showed that perfect imaging of a metamaterials lens is practically realizable, but only over a restricted range of parameters, such as lens thickness and periodicity of the structure of the metamaterials [18, 19]. As extensive numerical examinations have been performed, few experiments are performed correspondingly. Preliminary experimental evidence of the focusing ability of negative refraction index slabs has been realized, though, from a point source [20]. In this paper, we experimentally realized Perndry's superlens, with an analog in microwave optics [21, 22].

As a microwave optical analog, in our experiment, a Gunn diode microwave transmitter was first used. Typically, the output was a linearly polarized microwave at a wavelength of 2.85 cm for a frequency of 10.525 GHz. Later, we used a synthesizer to tune the frequency. Referring to fig. 1, we then used common double slits to simulate two apertures, so that the outputs from these two slits formed two separated sources. The slit width was 1.0 cm for both slits and the width of slit spacer was 1.4 cm. The aperture material was aluminum. The distance between the centers of the two slits was 2.4 cm, which was smaller than the wavelength, *e.g.*, 2.78 cm for a 10.8 GHz microwave. The crucial issue was: could we recover the double-slit structure from some distance away? If the width of the slit spacer and the slits were large enough, then a common double-slit interference could be identified, in which the resolution was still limited by the diffraction limit. This is typical, as seen in microwave optics experiment [23]. Here, however, if the slit spacer was not wide enough, common double interference would not occur and this double-slit structure would effectively become a two-source structure. The object plane was at the location of the plane of the two-source structure. Without LHM, we observed a common feature of diffraction and the two-source structure could not be resolved, as demonstrated below. In detection, to increase the resolution, we made an axial-mode 6-turn helical antenna as the microwave receiver [24], which was connected to a spectrum analyzer (HP 8563E, bandwidth: 9 kHz–26.5 GHz). The spacing between the turns of the helical antenna was 6.88 mm and the diameter of the helix was 8.8 mm. Microstrip-line impendence

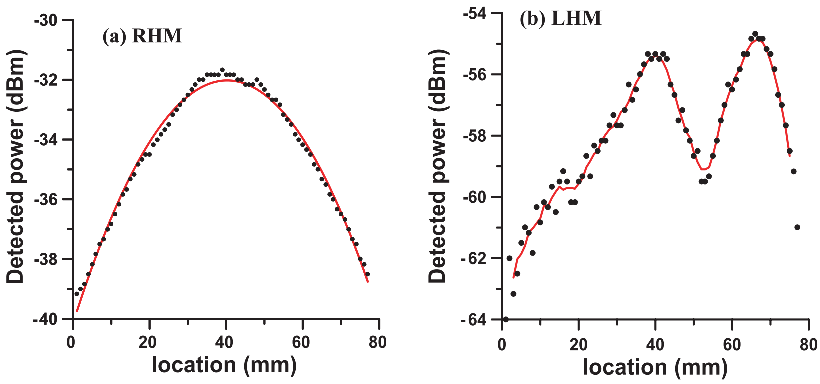

Fig. 2 – (Color online) Measured intensity profiles for (a) right-handed material (styrene pellets), and (b) left-handed material. The dots denote the experimental data and the solid line shows the fitted curves. In (a), a polynomial of second order is used for fitting, while in (b), we used the running average method with 5 data (window width).

matching was also implemented to improve the standing wave ratio (SWR) [25] at the desired frequency range for the helical detector. We used a vector network analyzer (Agilent 8720D) to verify the performance of the detector and the SWR < 2. In data acquisition we also used a translation stage to move the helical detector platform with a step of 1.0 mm. The locations of the effective detection points of the helical detector formed an image plane. Typically, the distance between the image and object planes was 8.0 cm. The experimental setup was 18 cm from the table surface, in order to prevent possible interference, due to reflection. With this configuration, we were able to resolve the structure. However, finer resolution was difficult to achieve, mainly because a smaller two-source structure scale was not easy to create with the current microwave source. We applied a synthesizer (Agilent 82731B; frequency range: 1–20 GHz) to drive the emitter. The LHM sample, used in the experiments, consisted of a two-dimensionally periodic array of copper split ring resonators and wires, fabricated by a shadow mask/etching technique, similar to that shown in ref. [3], on 1 mm thick circuit board material (FR4). The physical volume of the LHM cube sample was $14 \times 10.5 \times 4\,\text{cm}^3$. The LHM was confirmed to have a negative index, while common right-handed material, consisting of styrene pellets ($n = 1.30.05$), was used for the cross-check. For the LHM, the refraction angle was -53X; hence the index of refraction was -2.33 for the microwave at 10.5 GHz.

We believe that there are, at least, two key factors in achieving Pendry's superlens. We denoted the thickness of LHM as h, while distances of the LHM to the image and the object planes were a and b, respectively. 1) To realize Pendry's superlens, we found that the equality of $h = a + b$ was crucial, as implied by the numerical demonstration in ref. [1]. Different choices of a and b did not change the conclusion, provided that $h = a + b$ was satisfied. 2) Furthermore, the index of refraction had to be kept at -1. However, precisely realizing $n = -1$ was difficult. To fulfill the requirement, we tuned the microwave frequency to 10.835 GHz, such that $n \sim -1.0$ approximately. The experimental result of the common RHM (styrene pellets) is shown in fig. 2, where a broadly spread profile can be seen, indicating that the two-source structure (apertures) cannot be distinguished. With the LHM, on the other hand, a clear two-peak profile appeared, corresponding to the two-source structure, as shown in fig. 2(b). This difference is significant and important, since it reveals that sub-wavelength resolution is possible, although high-resolution capability (*e.g.*, using a wavelength of 356.3 nm to resolve

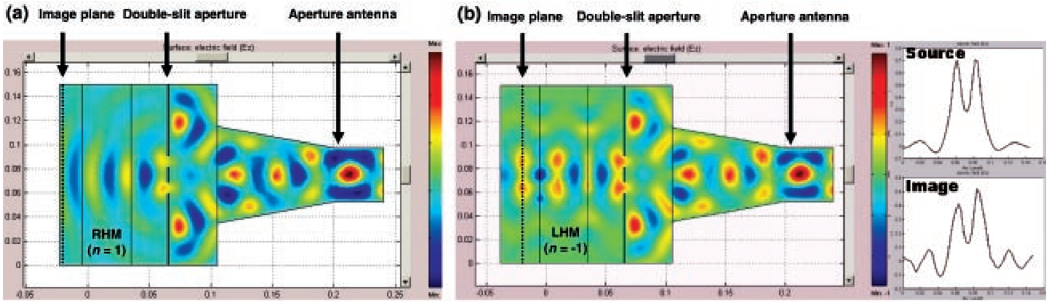

Fig. 3 – (Color online) Simulated field distributions for (a) right-handed material and (b) left-handed material, where the cross-sections at the object plane (source) and the image plane (image) are also displayed.

the structure of 80 nm) remains difficult. Practically, current measurement was limited by the resolution of the helical detector, while the precise operation of a refractive index at -1, was not trivial, in the least. Experimentally, the difference between the locations of the two peaks was 2.5 cm as indicated by the arrow, which is close to the designed spacing, of 2.4 cm. This difference, between the two peak locations, was also smaller than the electromagnetic wavelength of 2.77 cm. Thus, evidence of Pendry's superlens can be concluded from the appearance of the two-peak profile.

Next, we explored the experimental result by simulation, based directly on Maxwell equations. We utilized FEMLAB [26], a commercial electromagnetic-wave simulation package, to examine the correspondence. This package is a finite-element time domain solver of partial differential equations. For simplicity, we only used the two-dimensional simulation, *i.e.*, the mode of 2D, in-plane waves, and TE waves. First, one aperture antenna, with an emission frequency of 10.8 GHz, was modeled as the driving source. We then adopted a double-slit aperture to create the two-source structure. The double-slit aperture and the image plane are labeled in fig. 3 for reference. The widths of the slits and the slit spacer, and the distances, were kept the same as those in the real experiment. Simulation confirmed that our current experimental configuration was close to the limit for the onset of the two-source structure; there was no output if the width of the slit spacer, or the width of the slits, became smaller. In simulation, the boundaries, to where the electromagnetic wave eventually spread, were assumed to absorb the electromagnetic wave, *i.e.*, they were low-reflecting. The material property was specified by setting both the permeability and permittivity as equal to -1 in the simulation setting of the sub-domain mode [26]. For reference, we labeled the boundaries of the medium with thin solid lines as shown in the middle portion of fig. 3. Figure 3(a) shows the result, using the common material, where a broadly spread field profile, similar to the experiment, can be seen. On the other hand, with a negative-index LHM, where the permeability and permittivity are both -1, a recovery of the object, *i.e.*, the two-source structure, can be found on the image plane. The cross-sections of the source and the image are also shown in fig. 3(b) for reference. This electromagnetic-wave simulation provided us alternative evidence of Pendry's superlens.

In conclusion, we have provided experimental evidence of Pendry's superlens in a microwave regime, with metamaterial formed by a periodic array of split ring resonators and continuous wires. Additional numerical evidence is also included. It has been shown that LHM can lead to a superlens, with a resolution not limited by wavelength. This metamaterial is a medium with a negative refractive index in the X-band microwave range. Optical correspondence may be achieved in the nano-structure material, proposed by Dewar [27], in which a periodic array, based on nano-sized YIG material and metal wire was proposed as being a suitable candidate for a negative index of refraction medium, while Pendry proposed the direct use of a slab of silver [1]. Overall, this microwave optical analog serves to demonstrate the fundamental characteristics of electrodynamics, inherent in negative-index metamaterial. Our work shows that although Pendry's superlens can recover the object at the image plane, with a resolution beyond the wavelength limit, several critical requirements remain: *e.g.*, the distance relationship ($h = a + b$) must be retained and the index of refraction must be -1.

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