A Negative Reflective/Refractive "Meta-Interface" Using a Bi-Directional Phase-Conjugating Array

Catherine A. Allen, Kevin M.K.H. Leong, and Tatsuo Itoh

Department of Electrical Engineering, University of California, Los Angeles,
405 Hilgard Ave., Los Angeles, CA 90095-1594, U.S.A.

Abstract **— A negative reflective/refractive "meta-interface" using a bi-directional phase-conjugating antenna array is proposed. Negative reflection is due to the retro-directivity of the array while negative refraction is a consequence of the bi-directionality of the slot elements used in the array. A simple design of the interface is presented. The prototype demonstrates negative reflection and refraction in far-field and near-field measurements.**

I. Introduction

In the last few years, there has been an emergence of research in the analysis and design of novel materials with properties not existing in nature, or meta-materials. In particular, left-handed (LH) materials have recently attracted significant attention [1]-[5]. In the microwave community, a transmission line approach and applications of LH materials were independently proposed by two different groups [6]-[9].

So far, the emphasis has been on artificial structures, inherently inducing losses, bandwidth limitations and dispersion. This paper introduces the concept of "meta-interface" as opposed to meta-material. If a simple thin interface can produce effects similar to those of a complex interface between a conventional right-handed (RH) material and a LH material, propagation will occur mainly in a real media, avoiding the shortcomings of an artificial structure.

We propose here a simple realization of a meta-interface achieving both negative reflection and refraction in the form of a phase-conjugating array [10]-[11]. The paper is organized as follows. Section II describes the concept of the proposed meta-interface and the principle of its implementation. Section III presents the architecture and design of the phase-conjugating array. Section IV and V demonstrate, through measurement, the far-field and near-field behaviors of the interface.

II. Concept of Meta-Interface

Fig. 1 shows three possible cases of reflection and refraction at different interfaces: RH/RH, RH/LH, and the proposed interface. As shown in Fig. 1(c), with the proposed interface, both reflection and refraction are the reverse of the conventional case shown in Fig. 1(a), while

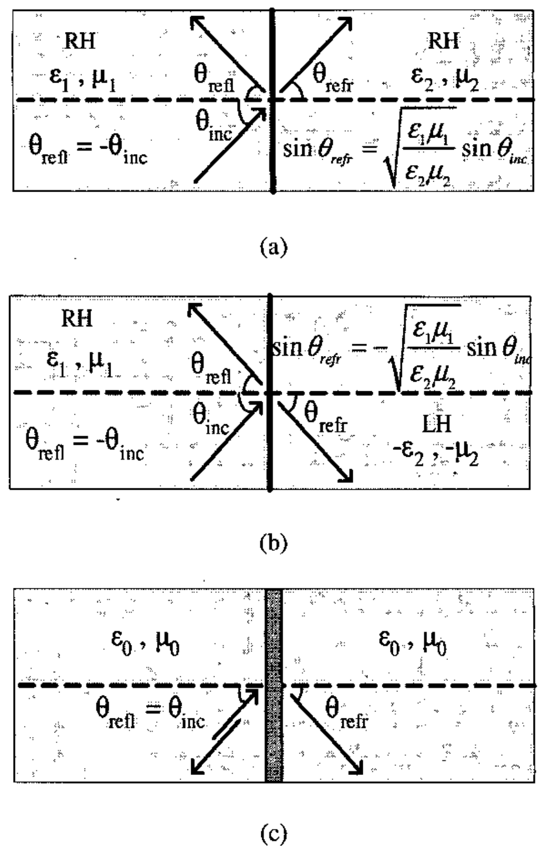


Fig 1. Reflection and refraction for (a) RH/RH, (b) RH/LH, and (c) proposed interface.

only refraction is reversed in the case of a RH/LH interface, as shown in Fig. 1(b).

The principle of the implementation of the interface operating in the far-field is illustrated in Fig. 2. The antenna array receives an incoming plane wave with incident angle θ_{inc}. The incident angle causes there to be a relative phase difference between the adjacent antenna elements and, as seen in the figure, the n^{th} element leads the $(n+1)^{th}$ element by $\beta d \sin\theta_{inc}$. After phase conjugation the n^{th} element lags the $(n+1)^{th}$ element by $\beta d \sin\theta_{inc}$, causing the reflected signal to have an angle θ_{refl}, equal to θ_{inc} and the refracted signal to have an angle θ_{refr} equal to $180° - \theta_{inc}$. Thus, this configuration produces an effect equivalent to the reversal of Snell's law. For clarity, Fig. 2 indicates two distinct arrays, one that receives the incident signal and radiates the reflected signal and one that radiates the refracted signal. The prototype, however, combines these receiving and transmitting sides into a single antenna array.

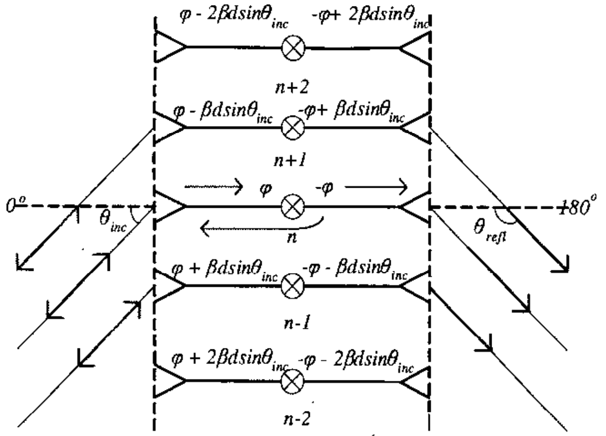


Fig 2. The principle underlying the implementation of a negative reflective / refractive interface.

The meta-interface also exhibits interesting effects in the near-field. In this case, the incident signal is no longer a plane wave and the refracted signal is focused in a lens-like effect. Unlike a conventional lens, however, a displacement of the source will cause an image displacement in the same direction as the displacement rather than in the opposite direction.

III. Meta-interface Circuit

A picture of the circuit is shown in Fig. 3. The interface is constructed of two main sub-circuits, the antenna array and the mixer array. The antenna array consists of eight slot antennas with operating frequency at 5.2 GHz. The slot antenna is utilized for its omni-directional radiation characteristic allowing for the use of a single antenna array for both the reflecting and refracting ends of the interface. The individual elements are placed a half-wavelength apart at 5.2 GHz in order to avoid grating lobes. The mixer array consists of eight Schottky diode mixers utilized for phase-conjugating heterodyne mixing. The mixer array is fed on the LO side by a corporate feed-line constructed with Wilkinson power dividers. The IF-RF side of the eight mixers is connected to the eight elements of the slot antenna array.

When operated in the far-field, the antenna array receives an incoming 5.2 GHz signal from a source located at an angle θ_{inc} from the broadside of the interface. The antenna array then feeds the RF end of the mixer. The LO end is fed by a signal of approximately twice the RF. The phase-conjugated IF signal is then radiated by the antenna array. Due to the phase-conjugation, the two main lobes of the transmitted pattern will be located at θ_{inc} and $180° - \theta_{inc}$, constituting the negative reflection and refraction of the meta-interface. Note that in measurement, while the LO is slightly greater than the RF in order to distinguish the IF, it can be operated with RF equal to IF. When operated in the near-field, the received signal can no longer be considered a plane wave. Phase conjugation in the process described above results in a maximum refracted power that will mirror the location of the source.

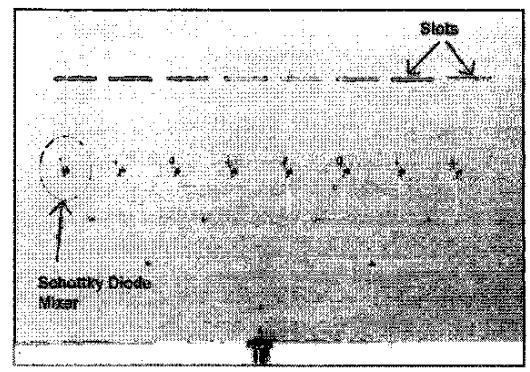
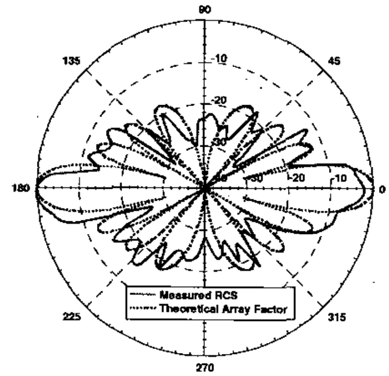


Fig. 3. Picture of front side of interface prototype. Slots on reverse side are indicated by black rectangles.

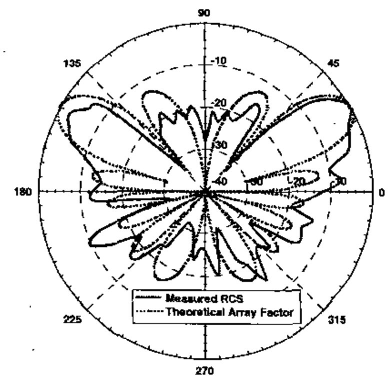
IV. Far-Field Measurement

To measure the bistatic RCS pattern of the meta-interface, a 5.2 GHz source was placed initially at 0° relative to the broadside of the array. The mixer side of the interface was fed with an LO of 10.42 GHz, resulting in a 5.22 GHz signal measured at the receiver. The source was then moved to -30°and +30° relative to the broadside. The measured bistatic RCS for all three cases are shown in Fig. 4. The array factor for an 8-element array is also included for comparison.

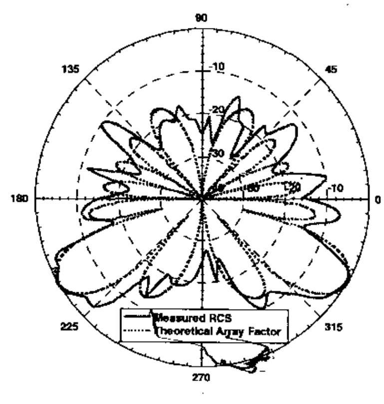
For the broadside case we observe that the bi-directionality of the slot antenna causes reflection at an angle of 0° and refraction at an angle of 180°. When the source is moved relative to the broadside, the negative reflection and refraction become apparent. For the -30° case, the main lobes are located at -30° and 210°, indicating negative reflection and negative refraction respectively. Similarly, for the +30° case there is negative reflection of angle +30° and negative refraction of angle 150°. Note that the RCS measurement closely resembles the theoretical array factor for an 8-element array. As this measurement was not performed in an anechoic chamber, the scattering due to the environment causes slightly erratic jumps in the pattern.



(a)



(b)

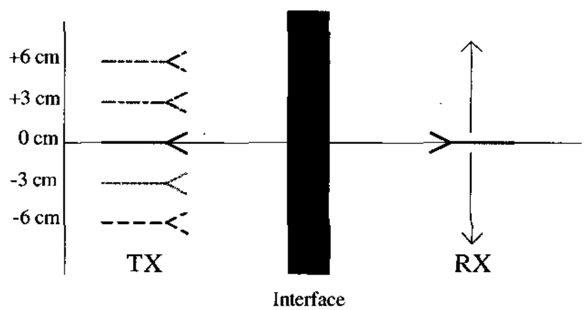


(c)

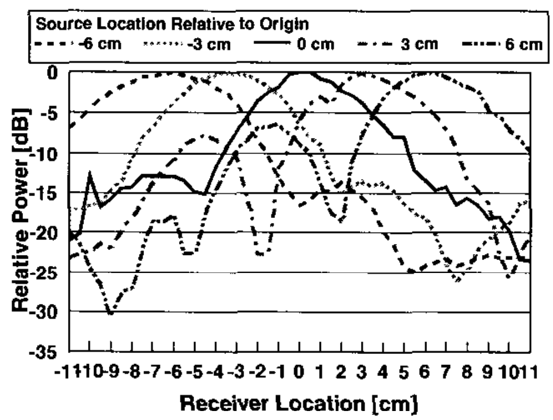
Fig. 4. Measured normalized RCS of meta-interface for source located at a) 0°, b) 30°, and c) -30°.

V. Near-Field Measurement

For the near-field measurement it was necessary for the source and the receiver to be located in the near-field of the array (less than 185 cm), but in the far-field of the slot antenna element (greater than 3 cm). The source and the receiver were placed 11 cm from the array. The set-up for this measurement is shown in Fig. 5(a). The source was initially normal to the midpoint of the array and we will refer to this position as the origin on the source side. The receiver was moved relative to the origin on the receiver side, measuring the received power along a path parallel to the interface. As in the far-field case, the source signal was 5.2 GHz, the LO was 10.42 GHz, and the received signal was 5.22 GHz. The measurement was made with the source at 0, ±3 cm, and ± 6 cm relative to the origin on the source side. Fig. 5(b) shows the received power versus the position of the receiver for the source at the locations described above.



(a)



(b)

Fig. 5. a) Configurations for six near-field measurements with source located at 0, ±3, and ±6 cm with respect to

origin and b) measured received power pattern for varying source displacements.

The figure indicates that a displacement of the source relative to the origin on the source side causes a displacement in the same direction of the peak received power relative to the origin on the receiver side. This mirroring of source and image demonstrates the converse of conventional lens behavior in which the source and image displacement are in opposite directions.

VI. Conclusion

A negative reflective/refractive "meta-interface" using a slot bi-directional phase-conjugating antenna array has been proposed. Measurement results demonstrated negative reflection and refraction in the far-field of the array and displacement of the refracted signal in the same direction as that of the source parallel to the interface in the near-field. These unusual effects may be exploited in quasi-optic beam-forming applications.

Acknowledgements

This work is part of the MURI programs "Scalable and Reconfigurable Electromagnetic Metamaterials and Devices" and "Multifunctional Adaptive Radio, Radar and Sensors (MARRS)." It is supported by the Department of Defense (N00014-01-1-0803 and DAAD 19-01-1-0496/956006143) and is monitored by the U.S. Navy/Office of Naval Research and the U.S. Army Research Office.

References

[1] V. G. Veselago, "The Electrodynamics of Substances with Simultaneously Negative Values of ε and μ," *Soviet Physics Uspekhi*, vol. 10, no. 4, pp. 509-514, Jan.-Feb. 1968.

[2] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser and S. Schultz, "Composite Medium with Simultaneously Negative Permeability and Permittivity," *Phys. Rev. Lett.*, vol. 18, no. 84, pp. 4184-4187, May 2000.

[3] D. A. Shelby, D. R. Smith and S. Schultz, "Experimental Verification of a Negative Index of Refraction," *Science*, vol. 292, pp. 77-79, Apr. 2001.

[4] M. Notomi, "Theory of Light Propagation in Strongly Modulated Photonic Crystals: Refraction like Behavior in the Vicinity of the Photonic Band Gap," *Phys. Rev. B*, vol. 62, no. 16, pp. 10696-10705, Oct. 2000.

[5] J. B. Pendry, "Negative Refraction Makes a Perfect Lens," *Phys. Rev. Lett.*, vol. 85, no. 18, pp. 3966-3969, Oct. 2000.

[6] A. K. Iyer and G. V. Eleftheriades, "Negative Refractive Index Metamaterials Supporting 2-D Waves," *IEEE-MTTInt'l Symp.*, p1087-1070, Seattle, WA, June 2002.

[7] C. Caloz, H. Okabe, T. Iwai and T. Itoh, "Transmission Line Approach of Left-Handed (LH) Materials," *USNC/URSI National Radio Science Meeting*, vol. 1, p. 39, San Antonio, TX, June 2002.

[8] C. Caloz and T. Itoh, "Application of the Transmission Line Theory of Left-Handed (LH) Materials to the Realization of a Microstrip LH Transmission Line," *IEEE-APS Int'l Symp.*, Vol. 2, pp. 412-415, San Antonio, TX, June 2002.

[9] L. Liu, C. Caloz and T. Itoh, "Dominant Mode (DM) Leaky wave Antenna with Backfire-to-Endfire Scanning Capability," *Electron. Lett.*, vol. 38, no. 23, pp. 1414-1416, Nov. 2003.

[10] L. C. Van Atta, "Electromagnetic Reflector," U. S. Patent 2908002, Oct. 1959.

[11] C. Y. Pon, "Retrodirective Array Using the Heterodyne Technique,"*IEEE Trans. Antennas Propagat.*, vol. AP-12, pp. 176-180, Mar. 1964.