Metamaterial-Based Device Engineering

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Metamaterials are artificial materials with unusual bulk properties [1], based on suitably designed arrays of complex resonant inclusions. By definition, metamaterials have properties not available in any of their constituents, or in any natural material, which emerge from strong wave-matter interactions and carefully engineered mesoscopic structures. In the past decade, metamaterials have opened several exciting directions in basic science. Relevant examples include the realization of artificial plasmas at microwaves, artificial magnetism in optics, negative refraction, cloaking and extreme scattering manipulation, and large wave control over surfaces significantly thinner than the wavelength. All of these features are not only opening fascinating new directions for basic research in optics, electromagnetics, acoustics, and beyond, but have also started to have important, direct applications in more applied engineering contexts. In the following, I briefly review some of the recent impact that metamaterials have been having in a few distinct engineering fields, overcoming some long-standing challenges for technology.

Cloaking and radio-transparent antennas

Invisibility has been a tantalizing concept in human culture for several centuries. With recent developments in metamaterial science and technology, the possibility of cloaking objects to incoming electromagnetic radiation has been escaping the realm of science fiction and has become a technological reality [2]-[3]. Beyond the exciting impact that cloaking concepts have been having in many field of basic science, cloaked objects can be of fundamental importance in several fields of engineering, including camouflaging applications and non-invasive biomedical sensing. Given inherent challenges in significantly suppressing the scattering from objects many wavelengths large with a passive coating [4], one of the most viable applications of cloaking technology focuses in the area of radio-frequency cloaked antennas or radiators, whose size is comparable to the wavelength, and therefore allows significant scattering suppression over large bandwidths. In our group, we have worked for several years on radio-wave cloaking applications [5]-[6], and we have recently shown that conventional antennas can be cloaked with suitably designed *meta-surfaces* to yield significantly reduced scattering from radio-waves, while preserving the possibility of transmitting and receiving signals, over large bandwidths of operation [7]. Figure 1, as an example, shows a cloaked dipole antenna for cellular communications, showing significantly suppressed radar cross section at all angles compared to a bare dipole, while being able to transmit and receive radio-frequency signals with good matching and isolation performance over the entire cellular band.

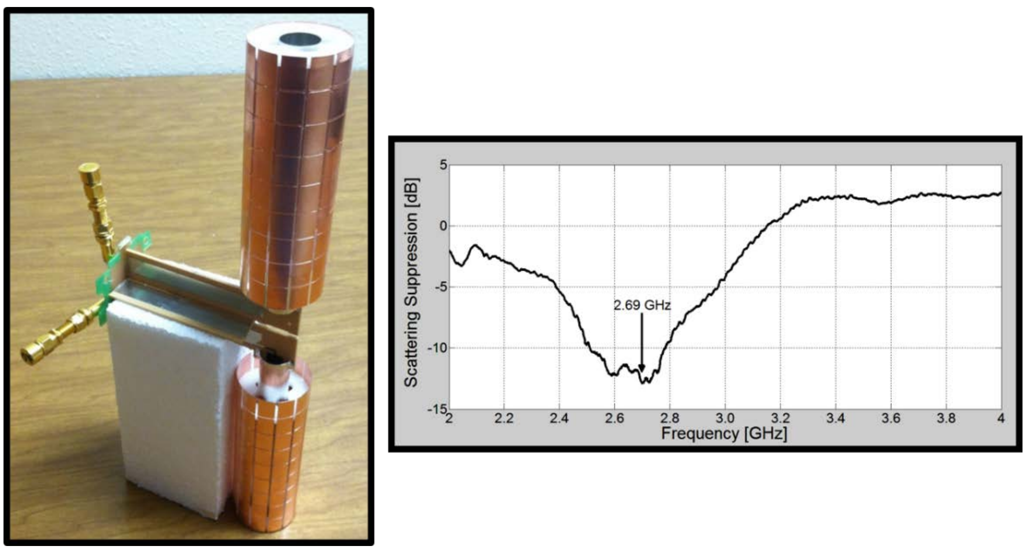

Figure 1 – A cloaked dipole antenna, which can transmit and receive signals, while producing significantly less scattering than a bare antenna. On the right: measured scattering gain, defined as the ratio (in dB) between a bare dipole and a cloaked one. Adapted from [7].

An invisible acoustic sensor

Cloaking a sensor or a receiving antenna presents fundamental challenges, because the same action of sensing requires extracting a portion of the impinging signal, and therefore creating a shadow [8]. A way around this fundamental limitation is provided by schemes that involve active elements. Inspired by recent advances in quantum mechanics in the area of parity-time symmetry, we have recently shown that it is possible to realize an invisible acoustic sensor with strong absorption properties by pairing a resonant sensor with its time-reversed image (Fig. 2) [9]. This device can absorb the entire incoming signal, yet at the same time it creates no shadow or reflection. The realized system was built by pairing in free-space two identical loudspeakers loaded by circuits with conjugate impedances, one passive, aiming at converting the impinging sound into a voltage across a resistor, the second active, aiming at emitting a signal, in sync with the impinging one, that would suppress shadows and reflections. This class of PT-symmetric sensors can be used also to realize loss-free negative index aberration-free planar lenses [10] and advanced cloaks [11].

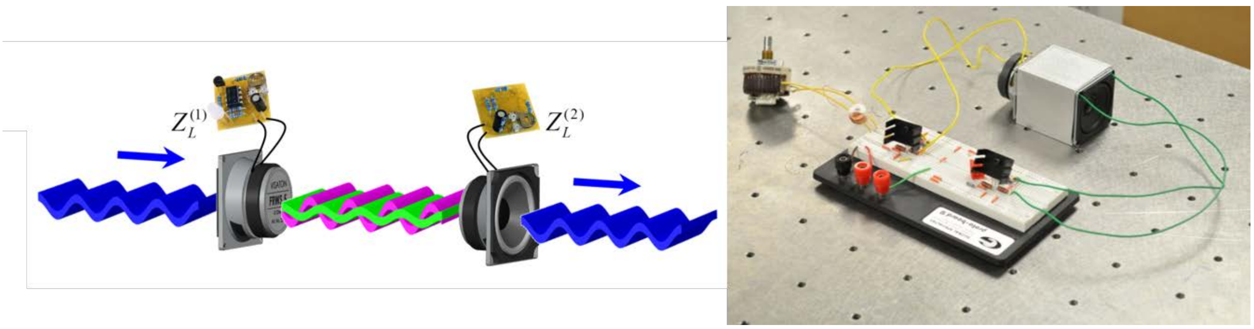

Figure 2 – An invisible acoustic sensor based on PT-symmetric meta-atoms in the form of loudspeakers loaded by circuit components with conjugate impedances. The setup enables a shadow-free efficient acoustic sensor. (Adapted from [9])

Non-reciprocal magnetic-free devices

Sound, light, and many other waves tend to travel symmetrically in space, implying that if we can send a signal from point A to B, we can typically send it also from B to A. This symmetry, known as reciprocity, boils down to the fact that wave propagation in conventional media, including light and sound, is time-reversible. Reciprocity is not necessarily desirable, especially when one wants to isolate a source from its echo, or separate signal flows traveling in opposite directions. Full-duplex communications, i.e., the possibility of transmitting and receiving signals from the same transducer on the same frequency channel, may be enabled breaking reciprocity, and it may lead to more efficient radio-wave communications, or better ultrasound imaging devices.

The most common way to break reciprocity is based on magnetic bias, which has however several challenges, including the use of scarce materials and the difficulty of integrate them onchip. We were recently able to prove that reciprocity can be broken by applying an angular-momentum bias to a metamaterial cavity, enabling the first-of-its-kind *circulator* for acoustic waves (Fig. 3) [12].

The system is a basic three-port device that allows one-way rotation of the input signals, from port 1 to 2, from 2 to 3, and from 3 to 1, while it prevents transmission in the opposite direction. Very large isolation (over 40 dB) was realized for airborne acoustic waves based on a suitably designed subwavelength acoustic ring cavity in which air was rotated simply using fans, and the cavity was symmetrically coupled to three acoustic waveguides, which formed the input and output channels of the device.

While it is interesting to see how such a basic active component can modify the way sound propagates, not always a mechanical motion of the filling material may be convenient or practical, especially when translating these effects to other types of waves, such as radio signals, which travel much faster than sound. In [13]-[14] these concepts were extended to an equivalent meta-atom in which fluid motion was replaced by proper spatio-temporal modulation of three strongly coupled resonators, realizing magnetic-free circulators for radio and ultrasound waves.

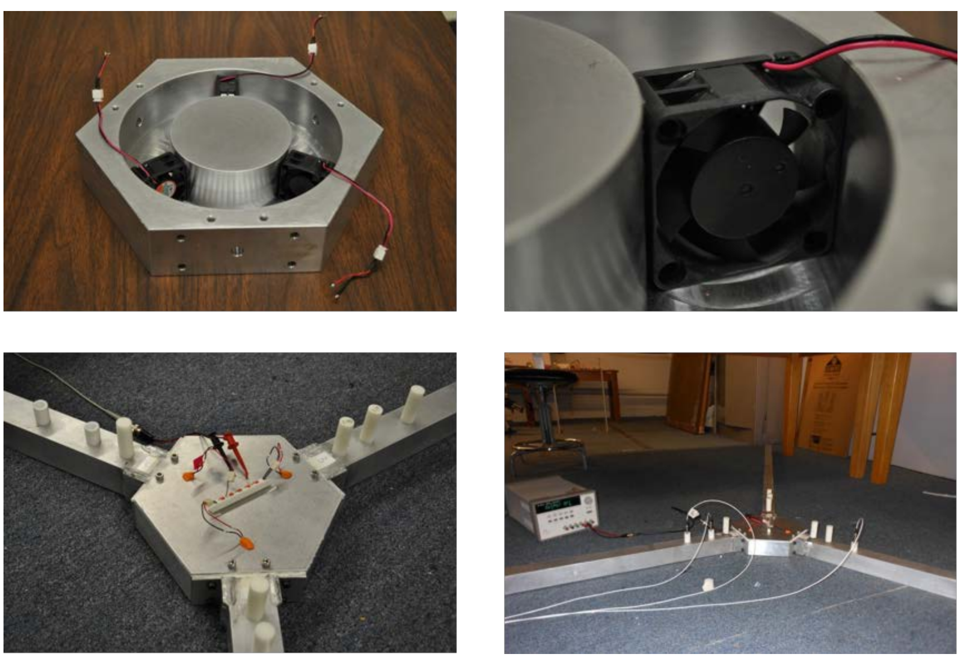

Figure 3 – A table-top circulator for sound, which allows breaking the symmetry with which acoustic waves typically travel in air. It is formed by a circularly symmetric cavity loaded with

three CPU fans that move air at a moderate velocity, enough to break reciprocity and enable large isolation. The cavity is connected to three acoustic waveguides carrying sound signals. (Adapted from [12])

Conclusions

The field of metamaterials has opened exciting directions in basic research in the last fifteen years, but recently it has also had a direct impact on applications, becoming a platform for important opportunities in applied technology, with implications in many engineering fields. Metamaterials are opening exciting directions for many applications, being able to overcome several of the conventional limitations of technology stemming from the use of conventional materials.

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