Nonlinear metamaterials: a new degree of freedom

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Varying the input power can tune materials to be either transparent or opaque at microwave frequencies.

Novel types of microstructured materials exhibit electromagnetic properties not found in natural matter. In particular, composite materials created by arrays of conducting wires and split-ring resonators can exhibit negative refraction.¹ These so-called ‘left-handed metamaterials’ were first mentioned as a theoretical curiosity 40 years ago, and although actual applications have not yet been realised, nonlinear metamaterials may enable manipulation of electromagnetic waves in previously unimaginable ways. They also have vast potential for future optical applications such as more efficient frequency converters, power limiters, and parametric amplifiers.

It is well known that a material’s response to electromagnetic radiation can be characterized by its magnetic permeability and electric permittivity. The product of these two physical characteristics defines the refractive index that measures how fast the material transmits light and how light is bent on entering the material: the higher the refractive index, the slower the propagation and the stronger the deflection. Metamaterials allow us to access even negative values of the refractive index. Importantly, they can also be designed with a spatially varying index of refraction. This is prerequisite for creating so-called electromagnetic ‘invisibility cloaks,’ the first of which—for microwaves—has already been designed.²

We have added a degree of freedom for metamaterial design by showing how the properties of a section of the material can be externally tuned by either applying an external constant magnetic or electric field,³,⁴ or application of DC biasing to embedded electronic components.⁵ We go further and suggest the concept of nonlinear metamaterials, whose properties are changed by electromagnetic waves. As an example, the material can be transparent for weak electromagnetic waves yet become opaque once the input power is increased. Nonlinear effects are uniquely useful in optics and telecommunications. This suggests that nonlinear metamaterials can offer very unusual functionalities.

Making nonlinear metamaterial

We first analyzed the properties of a hypothetical nonlinear metamaterial analytically⁶ in 2003. We showed that the hysteresis-type dependence (or memory effect, when the properties of the material depend on what has happened to it before) of the magnetic permeability on the field intensity allows dramatic changes to the material’s properties. As a first step toward creating tunable bulk nonlinear metamaterials we studied the dynamic tunability of the magnetic resonance of a single nonlinear split-ring resonator.⁵ These are key building blocks of metamaterials. Inserting a variable-capacity diode allows the split-ring resonator to be tuned by either a DC voltage or a high-power signal, and we recently demonstrated different tuning regimes.⁵ In addition, at higher powers the nonlinear response of the split-ring resonator becomes multivalued, indicating that the memory effect can potentially be observed in nonlinear materials.

We fabricated 2D nonlinear metamaterials by placing varactors (diodes whose capacitance depends on the applied voltage) in each of the split-ring resonators (see Figure 1). We noticed a very pronounced shift of the resonance and then mea-
Figure 2. Measured nonlinearity-induced suppression of a metamaterial’s transmission coefficient.

The transmission through the nonlinear metamaterial with wires and split-ring resonators for different power levels.\(^7\) We also observed intensity-suppressed transparency for frequencies just below the resonant frequency. The material is transparent for low-level signals but when we increase the power the frequency is shifted to the region of positive susceptibility and the material becomes opaque. As a result, we observe strong suppression of the beam transmission by 20dB (see Figure 2), in qualitative agreement with our earlier theoretical predictions.\(^6\)

**Conclusions and perspectives**

Research on left-handed materials recently emerged as a new area of physics and engineering and is now attracting rapidly growing interest worldwide. Left-handed metamaterials possess unique properties which set them apart from any material available in nature. They not only offer novel possibilities for practical applications and devices but also display unexplored and intriguing properties that challenge fundamental physical concepts. Our suggested mechanism for dynamic control over the properties of metamaterials offers an additional degree of freedom for engineering such materials and increased flexibility for potential future applications.

The main hindrance to metamaterials’ use in real-life applications is their absorption of electromagnetic waves. We expect that our nonlinear metamaterials will compensate for this absorption through parametric amplification and allow the creation of more efficient optical applications. Plans for future work include creating a tunable microwave invisibility cloak as well as designing nonlinear metamaterials for optical frequencies.

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Ilya Shadrivov is a research fellow in the Research School of Physical Sciences and Engineering. His current research interests are in left-handed materials, negative refraction, nonlinear properties of artificial metamaterials, and plasmonics.

**References**