# Drawn metamaterials - a scalable approach to fabrication

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**Abstract**

We use optical fibre drawing techniques to produce hybrid polymer/metal fibres with modified electric and magnetic response in the THz. The technique can produce kilometres of metamaterial, and can be scaled for operation in the infrared and even potentially in the visible spectrum.

## 1. Introduction

Structuring metals and dielectrics at the scale required for metamaterials can be challenging. In most cases, metamaterials are fabricated using planar lithography techniques which cannot produce large, volumetric metamaterials. This is particularly true at optical frequencies, but even at THz and microwave frequencies achieving volumetric rather than two dimensional samples typically requires manual assembly of two-dimensional metamaterial boards or sheets. We recently demonstrated that fibre drawing techniques can be used to fabricate arrays of wires with plasmonic response in the THz[1], and even arrays of slotted resonators with magnetic resonances in the THz[2]. The fabrication technique can be scaled for operation at shorter wavelength, well into the infrared and even visible spectrum. Using drawing techniques enables the fabrication of kilometres of metamaterial fibres. These fibres can contain intricate structures with sections of fibres being devices in their own right, or contain simpler structures that could then be “woven” into devices.

## 2. Fabrication and properties

The fabrication procedure is similar to that used for drawing of photonic crystal fibres, but with the inclusion of metals in the preform. We stack polymer (eg polycarbonate or polymethyl-methacrylate (PMMA)) capillaries and indium wires or sheets into a preform a few centimetres in diameter. The preform is then drawn in a polymer fibre drawing tower at relatively low temperatures (but above the melting temperature of indium) and high tension. The cross-sectional geometry of the preform is preserved but the outer diameter is reduced by more than an order of magnitude (Fig. 1(a)). The resulting fibres can be stacked and drawn again to reduce the size of the features further.

The simplest example of drawn metamaterial is the fibre array, with an effective permittivity along the fibres having a plasmonic response that can be adjusted through the diameter and separation of the wires [3]. Figure 1(b) shows an example of such a drawn fibre, with indium wires $8\mu$m in diameter separated by $100\mu$m. THz transmission measurements and simulations show such a fibre has a plasma frequency

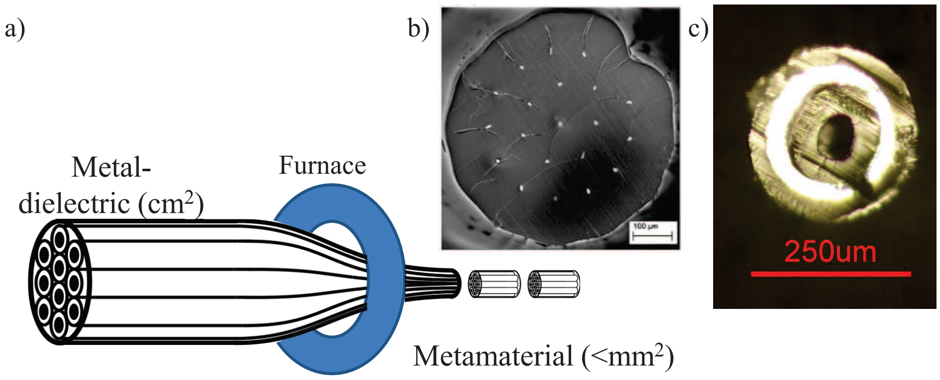

Fig. 1: a) A macroscopic preform is drawn to a metamaterial fibre; b) indium/polymer fibre with plasma frequency in the THz; c) Drawn magnetic resonator (the bright region is indium).

around 0.4THz[1]. The drawing technique can also be used with geometries more complex than wires, as for example in the slotted ring shown in Figure 1(c), which exhibits a strong magnetic resonance around 0.2THz with negative retrieved permeability. In both cases, kilometre lengths of metamaterial can be obtained from a single preform.

## 3. Conclusion

The fibres discussed above demonstrate that simple metamaterials can be drawn for operation in the THz spectrum. These metamaterial fibres can be used as such as filters or planar plasmonic waveguides. Assembling magnetic and electric resonators into more complex metamaterial devices within a single preform is also possible, for example for sub-wavelength THz waveguides[4], which would benefit from the fibre form factor, or for hyperlens designs across the fibre. While THz devices require dimensions on the scale of tens of microns, we have successfully drawn wires to sub-micron diameters, and it has been shown previously that features down to tens of nanometres can be fabricated[5]. The drawing technique can thus in principle be extended to operate at infrared wavelengths and even visible wavelengths. Slotted magnetic resonators for operation in the infrared should be possible yet challenging to fabricate, but for the visible spectrum only wire arrays can reasonably expected to be fabricated. An intrinsic limitation of the technique is that the geometry is invariant along the axis of the fibre, which restricts the range of possible metamaterials and in particular leads to strong spatial dispersion. However, a large range of devices can still be achieved, and we have shown that the technique should be suitable to produce macroscopic quantities of fibres that are invisible at optical wavelengths[6].

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