Silk Foam Terahertz Waveguides

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***Abstract*— Silk foam-based terahertz waveguides are fabricated using lyophilisation and casting techniques. This work is motivated by the lack of biocompatible waveguides for low-loss guidance of THz for applications in remote sensing in biomedical and agro-alimentary industries.**

I. INTRODUCTION

Silk is a unique kind of nature protein. In recent years this ancient material has been introduced into biomedical field as a promising biomaterial which opened a new era in the development of optical interfaces and sensors for biomedical applications. In the THz spectral range, split ring resonator-based metamaterials using silk films as a substrate were demonstrated [1] and applied as a conformal, adhesive edible food sensors to monitor changes in the food quality [2]. In this work [3], we present biocompatible THz waveguides made from silk foam. To our knowledge, this is the first time when biocompatible waveguides with sub 1 cm^{-1} losses are demonstrated in the mid-THz frequency range.

II. FABRICATION AND STRUCTURAL CHARACTERIZATION

Silk foams were obtained from a purified aqueous silk fibroin solution and lyophilised in a vertical freezer at -80 °C for several hours. Then the frozen sample was connected to a low vacuum system (mechanical pump). Eventually, the water sublimated and left behind the silk foam. We fabricated bulk silk foam from a conical tube test and silk fibers from a 5 mm-diameter plastic straw (Fig. 1(a)). Density measurements show a porosity (air fraction by volume) higher than 94%. Scanning electron microscopy of the bulk sample (Fig. 1(b)) reveal an intricate flaky structure of the silk foams. Namely, the crystallized silk fibroin form crumpled stacks of thin layers that are generally extending from the sample center towards the periphery. The individual silk layers are ~2 μm thick and there is 30-50 μm separation between layers. We believe that the radial pattern in Fig. 1 is caused by the directional dynamics of the freezing process, as well as circular shape of the container. In principle, controlled freezing could lead to design microstructure alignment that would impact both terahertz wave propagation and its polarization properties.

III. THZ CHARACTERIZATION OF THE SILK FOAM WAVEGUIDE

Fiber silk foams are investigated with a THz time domain spectroscopy setup. We measure the THz transmission through different length of samples (Fig. 2(a)). Using standard data fitting approach for cutback measurements and time domain fitting, we extract both the refractive index and the extinction coefficient in the THz region. We found a virtually constant refractive index of 1.0654 and the losses follow a square law ($a[cm^{-1}] \approx 3.1f^2$) (Fig. 2(b)).

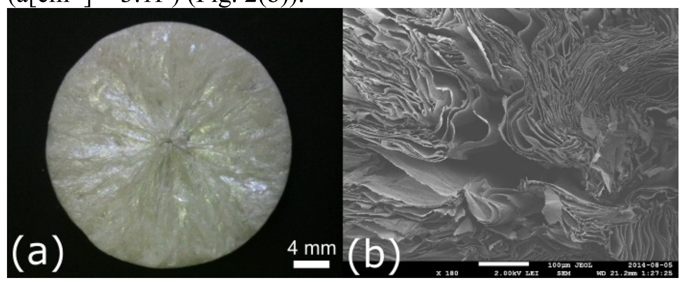

Fig. 1. (a) Photograph of the bulk silk sample and (b) SEM at the center of the sample revealing thin walls (bar: 100um).

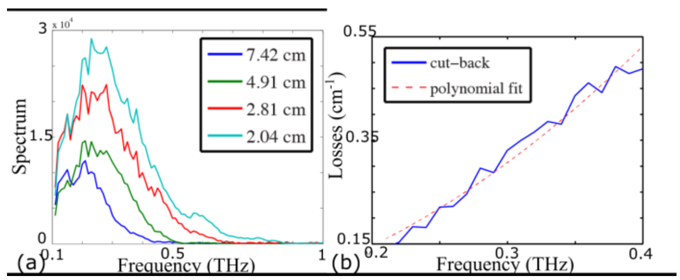

Fig. 2. (a) Cut-back measurements at different lengths of the silk fiber. (b) Calculated losses from the cut-back data.

IV. DISCUSSION

The absorption loss of silk foams in the THz spectral range is reduced by almost one order of magnitude compared to that of solid silk. In particular at 0.3 THz, we found a loss of ≈ 0.32 cm^{-1} while that of solid silk is ≈ 15 cm^{-1} [1]. Its main advantage compared to other waveguides is that it is biocompatible, biodegradable and it could be biofunctionalized with various materials. Moreover the foam porous structure can be useful for sampling of various biofluids using capillary effect for applications in biosensing for instance. This cannot be done with polymer waveguides.

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