Optical guided mode resonance filter on a flexible substrate

Peter Reader-Harris,[1]* Armando Ricciardi,[2] Thomas Krauss,[1] and Andrea Di Falco[1]

[1] *School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, KY16 9SS, United Kingdom*

[2] *Optoelectronic Division, Department of Engineering, University of Sannio, I-82100, Benevento, Italy*

**pjrh@st-andrews.ac.uk*

Abstract: We demonstrate the operation of a flexible optical filter based on guided mode resonances that operates in the visible regime. The filter is fabricated on a free standing polymeric membrane of 1.3 μm thickness and we show how the geometrical design parameters of the filter determine its optical properties, and how various types of filter can be made with this scheme. To highlight the versatility and robustness of the approach, we mount a filter onto a collimated fibre output and demonstrate successful wavelength filtering.

OCIS codes: (050.1950) Diffraction gratings; (050.6624) Subwavelength structures; (220.4241) Nanostructure fabrication; (250.5403) Plasmonics; (250.5460) Polymer waveguides.

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1. Introduction

Guided mode resonance (GMR) filters were proposed in the 1990s [1,2] as a novel way for providing a narrow linewidth wavelength response. In these filters, guiding and periodically modulated layers are judiciously arranged to create interference effects between the interfaces, to control the spectral features of transmission, reflection and absorption. GMR filters have mainly been used in the near infra-red wavelength regime, including for imaging applications [3, 4]. The visible spectrum is also being researched [5, 6], including filters with low angular dependence [7] and broad wavelength response [8]. Initially, GMRs were based on high contrast dielectrics, but the same scheme can be implemented in metals, allowing also the realization of extraordinary transmission effects [9] and perfect absorption [10]. Metals are normally associ-

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ated with high losses, limiting their use for producing narrow linewidth filters. This is because the linewidth (inversely proportional to the quality factor Q) of a plasmonic resonance is set by the material properties [11], and is generally low. Yet, incorporating a Fano resonance into the system can circumvent this limitation and generate much higher Q values [12–14]. Such a Fano resonance results from the interplay between a narrow resonance (e.g. a waveguide mode) and a broad resonance (e.g. a plasmon mode) [15, 16]. Highly efficient optical bandpass filters can result from this scheme [17], including filters with tunable resonances [18].

Here, we demonstrate the metallic GMR scheme on a flexible substrate. Flexible plasmonic structures for the optical regime have recently been demonstrated [19] and the advantage of flexibility includes the possibility of tuning the resonances after fabrication [20, 21], and placing the filter onto curved substrates. This proposed optical device belongs to the class of metasurfaces, being an extension of frequency selective surfaces [22]. These materials replicate one or more properties found in metamaterials whilst being only one layer thick. These include frequency selective surfaces with response independent of the angle of incident light [23], negative refractive index materials [24], and cloaking mantles [25].

One of the main challenges of fabricating flexible rather than rigid GMRs is the fragility of the waveguide layer, which has to be thin enough to support only a small number of waveguide modes. Here, we use a thin freestanding layer of polymer in the micron range, as shown in Fig. 1. The metal introduces a localized plasmon resonance that provides the Fano interaction with the substrate acting as the waveguide layer. The fact that the substrate is free-standing and flexible adds an important degree of freedom for the use of such filters in a variety of applications, such as in contact lenses or mounted on collimated fibre outputs as we demonstrate here. We point out that mounting flexible and removable devices onto the end of a fibre is a versatile alternative to fabricating permanent structures directly on the end of a fibre, e.g. by lithographic techniques or by focussed ion beam milling [26, 27].

In this paper we first examine how the geometry of the filter affects its properties, show the fabrication procedure and present the experimental results. Finally we discuss the results and draw our conclusions.

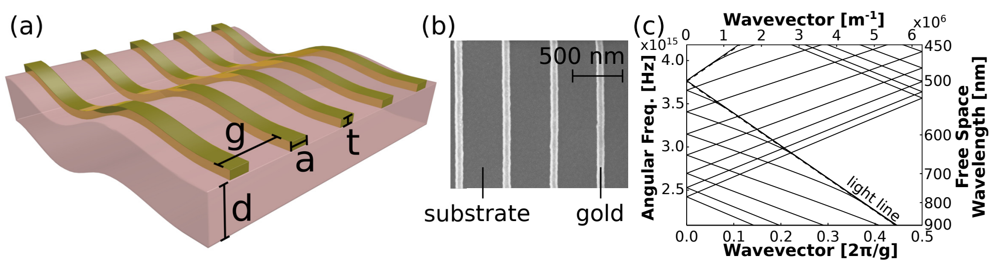

Fig. 1. a) Schematic of grating with relevant parameters labelled. b) SEM image of a fabricated grating. c) The bandstructure of a waveguide of 1.3 μm thickness with a grating of period 500 nm. The width of the plot is that of the first Brillouin Zone, and the frequency range is restricted to the visible spectrum.

2. Geometry and filter properties

The grating filter response is completely determined by the four parameters highlighted in Fig. 1(a), namely carrier thickness d, grating period g, wire width a and wire thickness t, along with the material properties. We chose gold for the grating because it combines lower loss in the visible spectrum with chemical inertness. We chose the polymer SU-8 for the substrate, which

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is an epoxy based polymer that can be spin-coated to submicrometric thickness when diluted with cyclopentanone. It has a refractive index of between 1.57 and 1.61 in the visible region.

The thickness of the waveguide slab (d) and the period of the grating (g) determine the bandstructure. An example for a typical bandstructure is shown in Fig. 1(c). The thickness of gold (t) does not change the bandstructure and the optical properties change very little for g between 20 nm and 100 nm. Much thicker gold can change the properties enormously, including absorption based applications, but these are not considered here. Using thin gold means that the empty lattice approximation is sufficient to calculate the bandstructure of the device as the gold grating can be treated as a perturbation on the surface of the waveguide slab. Figure 1(c) shows the bandstructure of a GMR with period g=500 nm, and waveguide thickness d=1.3 μm. This combination of parameters creates a device that supports a few modes which cross the Γ-point of the Brillouin Zone in centre of the visible regime. The width of the wires that make up the gold grating determines how the light is split between transmission, reflection and absorption. Since it is the the fraction of the surface covered with gold that determines this partition, the parameter considered here is the duty cycle (a/g). We used the rigorous coupled wave analysis (RCWA) method [28] to simulate the transmission, reflection and absorption properties of the filter across the full range of duty cycles at normal incidence. The results of the calculation are shown in Fig. 2. We used the complex refractive index of gold from Johnson and Christy [29].

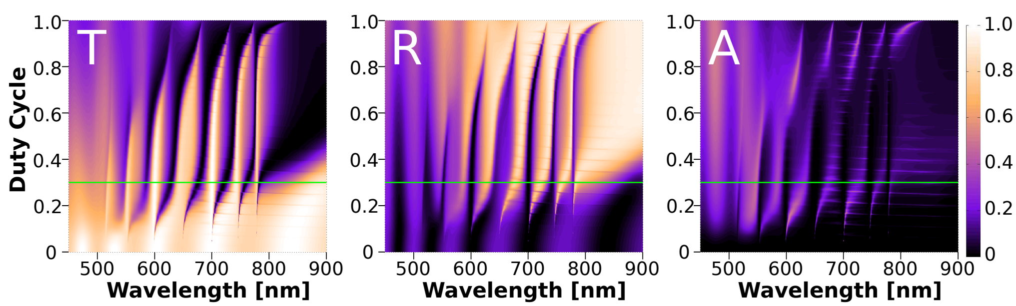

Fig. 2. Dependence of the transmission, reflection, and absorption properties of a filter with g=500 nm, d=1.3 μm, and t=30 nm on the duty cycle. The same colour bar is used for all three plots. The green lines show the duty cycle value of the fabricated sample (the T spectrum being shown in Fig. 4).

By tailoring the above parameters, it is possible to design many different types of filter based on this simple geometry. For example, narrow linewidth notch filters in transmission, or band-pass filters in reflection can be designed. If, alternatively, a transmission bandpass filter or reflection notch filter is required, then a high duty cycle can be used. Additionally, the absorption can be manipulated, and while thicker gold is needed to achieve perfect absorption [10], it is possible to fabricate thick gold structures that are highly transmissive [30].

3. Fabrication and characterization

We fabricated a sample to demonstrate the viability of the approach, following the recipe developed in [19]. We used an etch back process with electron beam lithography to define the pattern. We used a silicon substrate for mechanical support, a Microchem XP-SU8 release layer and a SU8 device layer that was cross linked with UV irradiation and baked at 100 °C for 4 min, onto which we evaporated a 30 nm thick gold layer. The pattern was defined by electron beam lithography, using 90 nm thick SU-8 layer as a negative resist. We developed for 45 seconds in ethyl lactate (EC) solvent and reactive ion etched for 8 mins at a pressure of 5×10^{-2} Pa,

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with 10 sccm of Argon plasma with 20 W power. The membrane was released by dissolving the sacrificial layer in *N*-methyl-2-pyrrolidone (NMP) for about an hour. The membrane detached and had to be transferred to a bath of water where it could be made to stay on the surface by the hydrophobic effect before being delicately mounted onto an acetate frame [31].

The samples were characterised both as suspended membranes and on top of a collimated fibre output. The former was performed using a modified Köhler illumination system [32, 33]. The grating transmission is strongly dependent on the incident angle, hence Köhler illumination with a low angular divergence was required. We estimate an angular divergence of 2.6° for our system. The sample was held on a computer controlled rotation mount between two 50× long working distance objectives and an Ocean Optics 2000+ USB spectrometer was used to acquire the spectra.

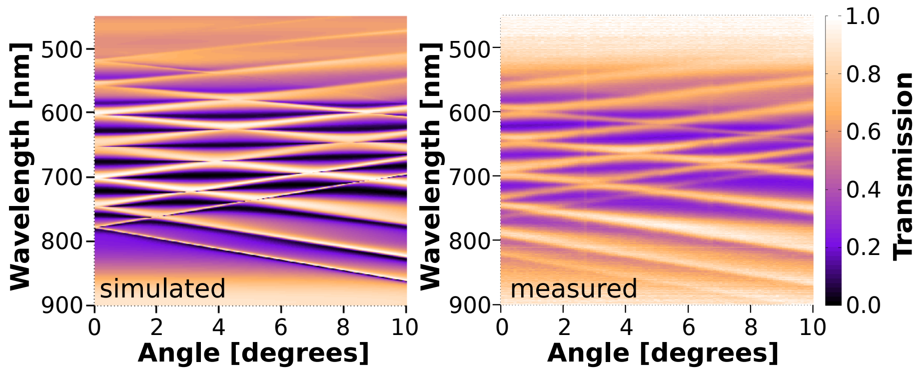

Fig. 3. Simulated (left) and measured (right) angle resolved spectra showing the bandstructure of the sample: g=500 nm, d=1.3 μm, t=30 nm and a=150 nm.

For the experiment, we selected a duty cycle of 30% for a transmission notch filter, as an example to demonstrate a proof-of-concept for this technique. The sample's transmission spectrum was measured in the angular region of interest from normal incidence to 10°, at 0.1° intervals, to build up a bandstructure of the filter. We show a comparison of the simulation, using RCWA, and the measured angular dependence of the sample in Fig. 3, showing good agreement. Some of the narrowest features are not very well reproduced in the experiment, which we associate with the angular spread of the light beam and experimental imperfections.

Next, we characterized the filter mounted onto the end of a collimated fibre output. The fibre was terminated by a collimator (Thorlabs F260SMA-B) and a linear polariser (Thorlabs LPVISE2X2) cut to size and attached to the collimator. Aluminium foil with a small hole ($7\mu m$) was used as a spatial filter to isolate the signal passing through the filter from the background and to support the polymer membrane. The filtered fibre's output was normalized to the same pinhole without the filter present. Figure 4(a) shows a photograph of the fibre-mounted membrane with an expanded view of several gratings scattering ambient light. Only one of them is aligned with the aluminium foil aperture. Panels (b)-(d) of the same figure show the optical response of the fibre-filter sandwich, as calculated with RCWA simulation and measured in free space and on the fibre, respectively. The simulated curve was extracted from Fig. 2 allowing an input angle of 5.7° around the normal incidence. This was done to take into account the angular spread of both the free space setup and of the fibre collimator. We register an excellent agreement between the two experimental curves, witnessing the robustness of the approach. Minor disagreements are also due to residual polarization and angle misalignment between the two experimental conditions.

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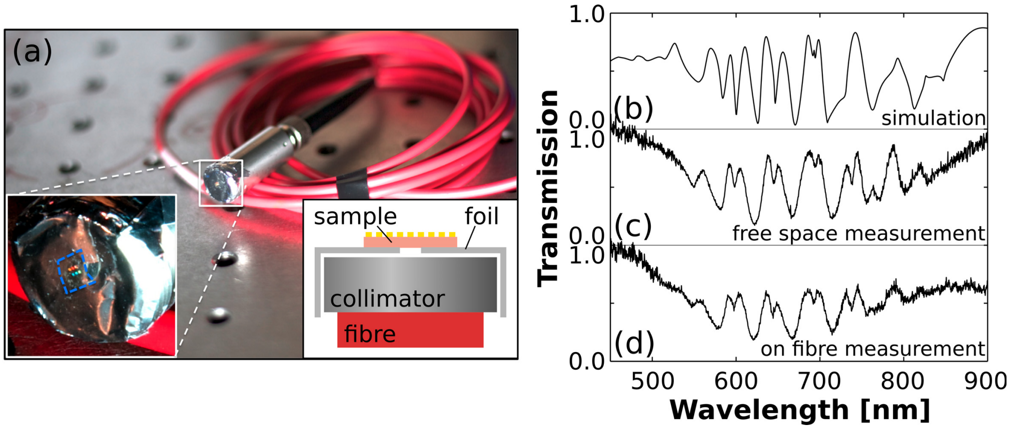

Fig. 4. Direct filtering on top of a collimated fibre output. The fibre, with insets showing size of the membrane (left) and mounting geometry (right) in shown in (a). The simulated, free space measured, and fibre mounted spectra are shown in panels (b)-(d).

4. Discussion and conclusions

We have fabricated and demonstrated the use of a flexible metallic GMR filter on the end of a collimator-terminated fibre, and seen that a filtered output can be achieved with inexpensive components. We used electron beam lithography for prototyping, which can produce samples up to a few square centimetres but this same filter could also be fabricated using nanoimprint lithography [34], which can also be applied to flexible substrates [35]. Having a flexible substrate makes this filter a strong candidate for being used in situations where movement or wrapping is required, such as on the end of fibres, either for filtering or using the grating to couple light into an external device. Curved gratings are desirable for their focussing properties, and the flexibility of the substrate allows tuning rather than a response set at fabrication time [36].

As Fig. 3 shows, GMR filters in general have a highly angle dependent response. However, GMR based filters with almost no angular dependence on transmission have been fabricated [7, 37] and require engineering the bandstructure so that flat bands are found at the centre of the Brillouin Zone. Reducing the number of waveguide modes could also increase the free spectral range of the device. Further investigation will focus on the fabrication of angle independent filters and robustness to the polarization, particularly for direct use on the tip of a fibre.

In conclusion we have demonstrated the fabrication of a flexible filter based on the interaction between the guided modes of a polymeric membrane and the plasmonic modes of a metallic grating. To highlight the advantage of having a supple and deformable substrate, we have wrapped a specific filter realisation on the tip of a fibre, showing that this does not compromise the operation of the device. This opens the door for further exploration; the research community can now proceed with confidence and design more application-targeted filter functions for on-fibre operation. Once the filter is mounted, the system requires no further care than is required for handling conventional optical fibres, and we note that the filters can be mass produced and are easily applied by the end-user, highlighting the potential for use in low-cost applications where a single fibre can be used for multiple experiments by changing the fibre filter termination.

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