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Steering and filtering white light with resonant waveguide gratings

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ABSTRACT

A novel thin-film single-layer structure based on resonant waveguide gratings (RWGs) allows to engineer selective color filtering and steering of white light. The unit cell of the structure consists of two adjacent finite-length and cross-talking RWGs, where the former acts as in-coupler and the latter acts as out-coupler. The structure is made by only one nano-imprint lithography replication and one thin film layer deposition, making it fully compatible with up-scalable fabrication processes. We characterize a fabricated optical security element designed to work with the flash and the camera of a smartphone in off-axis light steering configuration, where the pattern is revealed only by placing the smartphone in the proper position. Widespread applications are foreseen in a variety of fields, such as multifocal or monochromatic lenses, solar cells, biosensors, security devices and see-through optical combiners for near-eye displays.

Keywords: beam steering, white light source, up-scalable fabrication, resonant waveguide grating, guided mode resonance

1. INTRODUCTION

Resonant waveguide gratings (RWGs)[1] are structures of high interest used in a variety of applications such as filters,[2] biochemical sensors,[3] light absorbers,[4] security devices,[5] to name a few. These resonances were first observed by Wood in 1902 in the form of anomalous diffraction phenomena in grating structures.[6] Hessel and Oliver in 1965[7] started to differentiate anomalous diffractions in two types: the Rayleigh type, which is the classical Wood's anomaly, and the resonance type. The resonance anomalies in the form of coupled mode resonances were then systematically analyzed in 1990s.[8] In literature, RWGs have been called in many different ways: guided mode resonances,[8] leaky mode resonances,[9] corrugated waveguides.[10] All these terms express the main physical property of these structures: the diffracted wave from the grating is transferred as coupled mode in the waveguide material, it efficiently interacts with the incoming wave in a leaky process and it is released. In a finite-length grating, part of the mode can be in-coupled in the waveguide, acting as incoupler.

Standard RWGs with single periodicity cannot be applied for beam steering, because the beam deflection is only at the zeroth order (either in transmission or reflection).[11] However, it is possible to engineer a RWG made with two adjacent gratings having different finite-length periods to create a functional beam-steering element, as described later in this paper.[5]

Here, we first provide the reader different types of RWGs and a description of the single mode regime. Then, we describe the unit cell made with two RWGs that can be used to engineer a colorful label for optical security and can be seen only by positioning a smartphone in a specific spatial position. Finally, we provide some fabrication techniques and we show the fabricated device.

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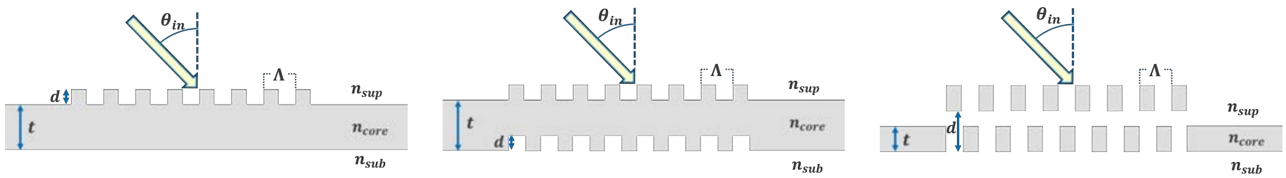
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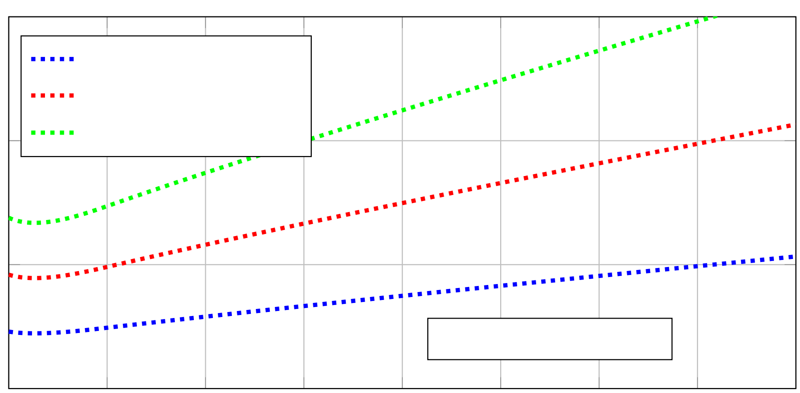
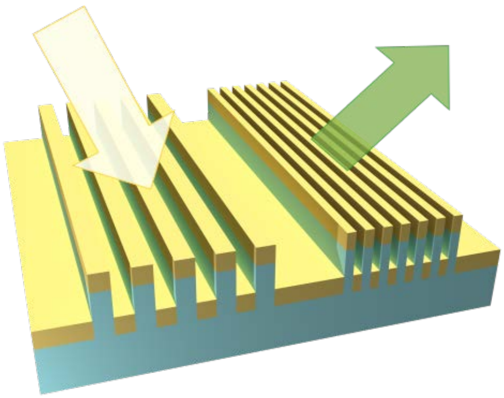
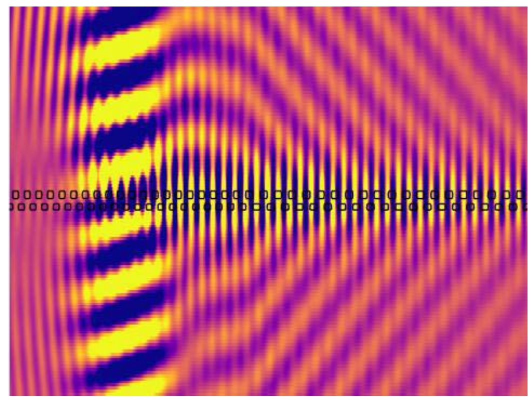
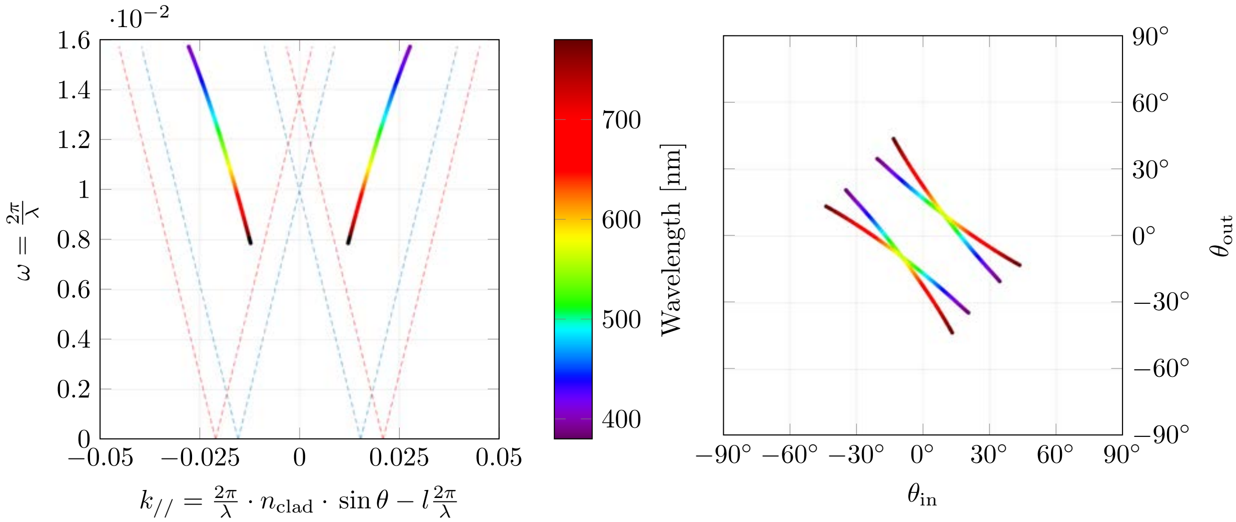






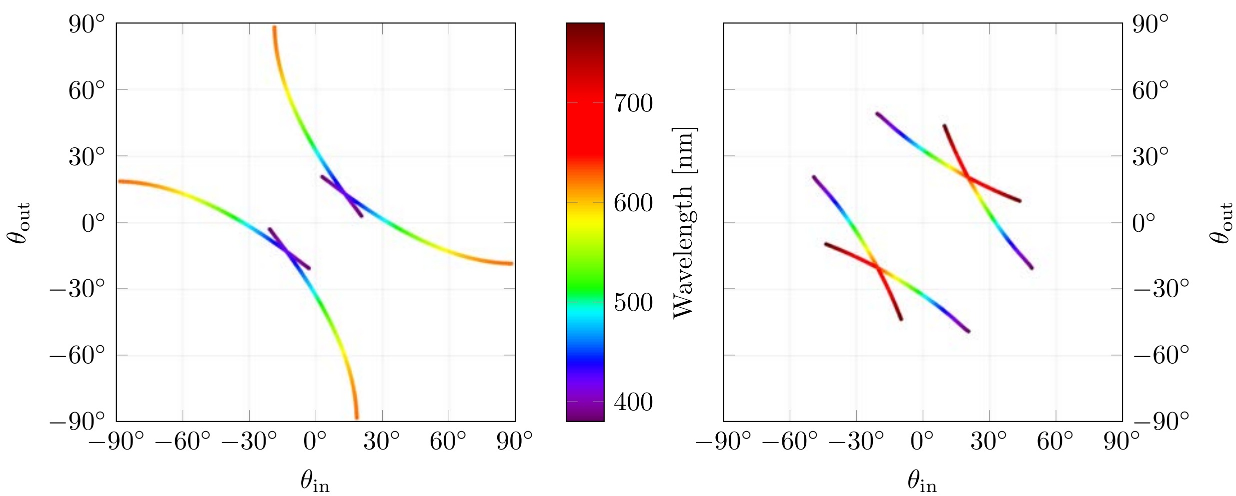


(a) Dispersion plot of a typical unit cell.

(b) Angular dispersion of a typical unit cell.

Figure 4: Unit cell made with two RWGs (specifications reported in Table 1). One RWG is responsible for in-coupling a spectral portion of the incident beam that is then out-coupled from the second RWG.

The dashed lines in Fig. 4a represent the dispersion of the first diffraction order of the RWGs in the limit case where the incident or steered light is at ±90°, red for the first grating (responsible for in-coupling the incident light) and blue for the second one (responsible for out-coupling the steered light). By changing the angle, the slope of the diffraction lines changes and they can intersect the dispersion curves of the waveguide, allowing the in-coupling/out-coupling of specific spectral ranges at given angles. The same information is highlighted in Fig. 4b, in terms of angular relation of the in-coupling and the out-coupling beams. By engineering different combinations of periods and orientations of the unit cells, it is possible to obtain the redirection of a beam for a specific color at any desired angle. For example, in Fig. 5 the angular dispersion graphs of the same unit cell but with different Λ_1 are reported, to show the versatility of the system.



(a) $\Lambda_1 = 200$ nm

(b) $\Lambda_1 = 600$ nm

Figure 5: Angular dispersion graphs of the same unit cell (with specifications in Table 1) but with different Λ_1.

4. ENGINEERING OF AN OPTICAL LABEL DETECTABLE WITH A SMARTPHONE

It is possible to take advantage of the beam steering property shown in the previous section to design a beam steering device that can be used in a variety of different fields. In this paper we show the implementation for an optical security device, where we design and fabricate three transparent structures that show uniform colors (i.e. red, blue and green) only by using a standard smartphone located in a specific spatial position on top of them.

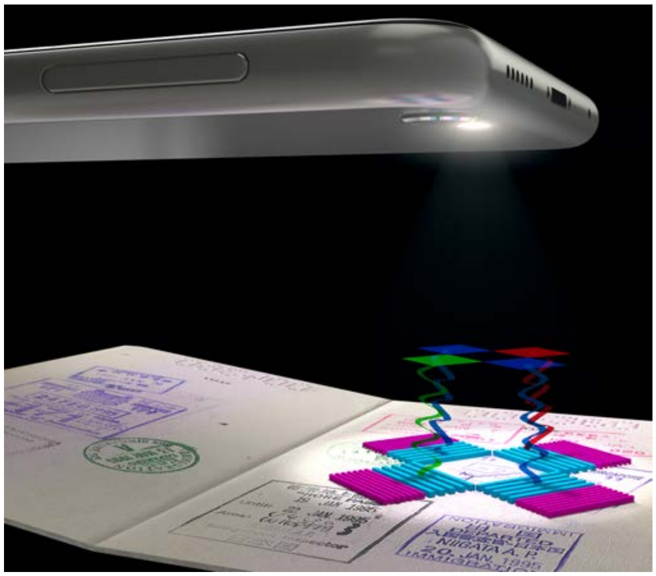


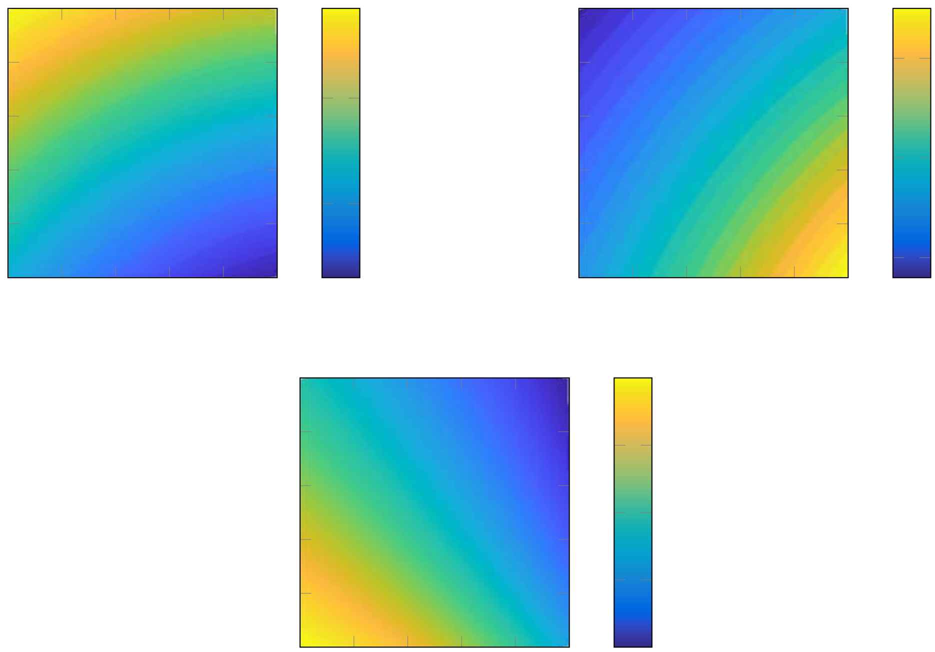
Figure 6: Artist's concept: optical security label made with RWGs that reveals a hidden pattern by using the flash and the camera of a smartphone in a specific spatial position. Image courtesy of Giorgio Quaranta.

For each realization, we engineer a flat surface of 1x1 cm^2 composed by more than 20.000 unit cells of two RWGs, where the white light coming from the flash of the smartphone is spectrally filtered and in-coupled in one RWG. The other RWG of the unit cell is responsible to out-couple the guided mode oriented towards the camera of the smartphone. Moreover, all the unit cells have been designed to create constructive interference of all the out-coupled beams in the position of the camera of the smartphone, where they are focused.[5] In particular the system is in off-axis configuration, since the angle between the source (i.e. the flash) and the observer (i.e. the camera) is non-zero. Moreover, the engineered surface works in conical illumination, because the grating grooves are not perpendicular to the incoming light.

The first step is to engineer the position, orientation and periods (Λ_1 and Λ_2) of the different unit cells. The known parameters are the position of the light source (i.e. the flash of the smartphone), the position of the observer (i.e. the camera of the smartphone), the desired waveguide thickness (for fabrication reasons the coating has to be the same on the whole device) and the refractive indexes of the materials used. In Fig. 7 the engineered values for the periods of the gratings and the orientation of the unit cells are reported.

The fabrication of the engineered device starts from the creation of a master with ebeam lithography. It is possible to notice in Fig. 7 that, for the case of the red label, the range of grating periods is relatively broad (between 280 nm and 440 nm), as well as the possible grating orientations (from 20° to 60°): a special custom ebeam pre-fracturing is required in order to achieve a fast but reliable ebeam lithography step. By properly tuning this process, it is possible to expose a surface of 1x1 cm^2 in less than 5 hours.

After developing the resist in TMAH solution, the master is then replicated on a Ni-shim and then embossed on a thin foil with hot embossing. The waveguide layer of ZnS is then deposited with PVD. Finally, the device is glued on a business card and encapsulated. In Fig. 8 is reported a picture of the business card with the hidden label and a figure taken with the smartphone properly positioned. The pattern is almost invisible by naked eye, and it has very small diffraction noise.

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