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► **To cite this version:**

G. Magno, M. Grande, Béatrice Dagens, Olivier Gauthier-Lafaye, A. d’Orazio. Guided Mode Resonance-Based Transparent Metasurfaces for Selective Multi-Color Reflection. 23rd International Conference on Transparent Optical Networks (ICTON 2023), Jul 2023, Bucharest, Romania. pp.1-4, 10.1109/ICTON59386.2023.10207202 . hal-04240556

HAL Id: hal-04240556

<https://laas.hal.science/hal-04240556v1>

Submitted on 13 Oct 2023

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Guided mode resonance-based transparent metasurfaces for selective multi-color reflection

G. Magno^{1,*}, M. Grande¹, B. Dagens², O. Gauthier Lafaye³ and A. D'Orazio¹

¹*Department of Electrical and Information Engineering (DEI), Polytechnic University of Bari, Bari, Italy*

²*Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies, Palaiseau, France*

³*LAAS-CNRS, Université de Toulouse, CNRS, INSA, UPS, Toulouse, France*

* e-mail: giovanni.magno@poliba.it

ABSTRACT

Metasurfaces enable precise and efficient control over light's angular-spectral properties, making them crucial for developing augmented reality displays for information visualization. In this contribution, we will focus on the design of transparent metasurfaces that use guided mode resonances to achieve polychromatic selective reflection, specifically for wearable augmented reality systems. These metasurfaces may be valuable in the realization of near-eye visual aids in support of individuals with cognitive impairment issues.

Keywords: Metasurfaces, augmented reality displays, guided mode resonances, near-eye visual aids.

1. INTRODUCTION

The nearly linear increase in the average age of the world's population is emerging as one of the most significant social challenges of this century [1]. The natural functional, physical, and cognitive decline accompanying ageing can find relief in new technological solutions devoted to improving the quality of life. Some application areas have considerable importance in promoting "active and healthy" ageing within their own environment, such as those related to the autonomy, mobility, and safety of elderly and/or frail individuals, while respecting their privacy and individual dignity.

Electromagnetic field-based technologies can have a great impact on improving quality of life. Radiofrequency to optical frequency systems can be invaluable in increasing the ubiquity of connections, both for the implementation of location and navigation systems and for the implementation of sensitive elements. Optical frequencies in the visible are safe for the human eye (within appropriate power levels) and can be used for both illumination, information display, and communications (see, for example, LiFi systems).

In this context, new human-machine interfaces (HMIs) are crucial as they serve as a direct boundary between the systems that produce the information and the users themselves. HMIs can be precious in case of cognitive impairment and sensory loss [2, 3]. Especially in cases of cognitive impairment [4], being able to clearly and effectively present visual information (e.g., in support of indoor navigation, by signalling a direction to take or avoid, or in support of home safety, by signalling hazards) can be a tremendous support to individuals affected by this condition [5–7]. Such visual information can aid understanding and decision-making even in the presence of varying degrees of cognitive impairment, which would have a significant negative impact on quality of life unless properly supported or compensated.

Visual information can be provided to observers through augmented reality (AR) displays, which allow them to see images, symbols, and text superimposed on the entire "natural" scene with which the observer is standing and interacting. Visual and visual-textual stimuli such as photos, memory books and wallets, reminder cards, pictograms, video content, and other visual tools can help with word-finding and communication during conversations [8] as well as improving their decisional capacity [9], especially in mild to moderate dementia conditions. Besides, such visualization systems are of central interest to a variety of fields, ranging from applications related to Industry 4.0 [10], vehicle driving aids [11, 12], to defence.

Augmented Reality systems require a supporting surface (such as, for example, the lenses of a pair of glasses, a windshield, the visor of a helmet, etc.) that is sufficiently reflective for some specific wavelengths and transparent for the remaining visible spectrum. This allows the desired information to be presented to the observer without compromising the brightness or colorimetric perception of the scene. At the heart of the system is a near-eye display, suitably tilted or shaped, mounted on top of a rigid wearable support like a pair of glasses. Additional optics may be included for magnification or for manipulating the light path. The visual information is then projected on the display by means of a laser projector or an LCD display.

Ivan Sutherland's first head-mounted AR prototype was devised in 1968 [13] and was given the moniker "Sword of Damocles" because of its weight and the fact that a portion of it was suspended from the ceiling. Since then, other systems with progressively smaller sizes, lighter weights, and better wearability have been presented [14, 15]. Though many companies and research centres are presenting their own systems, no final product has yet been made available to the general public. Several parameters need to be optimized at the same time to provide

perfect natural vision without any user discomfort, and this entails a challenge that still requires a proper solution. Of course, an ideal display should at once be small, lightweight, easy to wear, and should have enough resolution, a large field of view, a wide eyebox, absence of the vergence-accommodation-conflict [16], enough brightness and colour expression capacity. Visual acuity is ability to perceive and recognize small details with naked eye. Regardless of the distance between the screen and the eye, it requires a minimum resolution of 1 arcmin, which in turn corresponds to a display resolution of 60 pixel per degree. Near-eye displays can be obtained by exploiting waveguides [17–19], refractive freeform optics [20, 21], metasurfaces [22, 23], pinlight [24], holography, transmissive mirror devices and other approaches, and even based on their combination. In this contribution we will focus on metasurface-based near-eye display. Metamaterials offer unprecedented angle-spectral control over electromagnetic waves interacting with them. Whether they are purely dielectric [25–27] or plasmonic [28–34] in nature, the meta-atoms that form the periodic unit of metamaterials enable an unparalleled control of electromagnetic waves on dimensional scales comparable to wavelength or smaller. Similarly, metasurfaces, two-dimensional equivalents of metamaterials, promise to overcome the angle-spectral limitations of purely refractive surfaces while offering extremely smaller form factors. Besides, metasurfaces can be used in conjunction with other tools like nanoantennas [35, 36], mode coupling [37–40], guided-mode resonances [41], Pancharatnam–Berry phase [42], freeform optics [43], etc. to permit such arbitrary manipulation of the optical wavefront. For instance, the metaform paradigm combines metasurfaces and freeform optics into a single flat optical device [44, 45].

In the context of supporting medium to severe cognitive impairments, a near-eye display should be able to selectively reflect at least two colours (for example, red and green) to effectively represent information while allowing the light spectrum to pass by unhindered over the other colour components, making it sufficiently transparent and chromatically neutral (must not alter colour perception). In order to engineer the spectral response and create a single metasurface with spectral peaks in reflection centred at the wavelengths corresponding to the primary colours, we want to take advantage of the paradigm of guided-modes resonances [46]. From the point of view of a near-eye display, a diffraction grating, placed near a waveguide, plays the role of a phase adapter between the incident wave and the mode supported by the guide, allowing guided modes to be excited by direct illumination. Thus, a resonance arises from the coupling between the diffracted fields from the grating and the leaky modes that can propagate in the guide. Guided-mode resonance-based filters (GMRF) have been shown to be particularly suitable for tailoring the transmission properties of an interface to design colour filters characterized by a narrow linewidth and high efficiency. Dielectric grating-based structures, particularly 1D ones that produce a single reflecting colour filter for display, have proven effective in numerous studies [47–49]. Besides, multiple guided-resonances have been demonstrated in the NIR spectral domain by exploiting either multimode waveguides [50] and 2D crossed gratings [51].

Here we propose a structure that exploits such multiple resonances in the visible spectral domain to selectively reflect two or more colours simultaneously in near-eye displays. It consists of an asymmetric waveguide constituted by of a h -thick SiN film on a SiO₂ substrate and a 1D subwavelength grating of period p , with t -thick SiN ridges of width w , placed on its top. The structure, whose sketch is shown in Fig. 1(a), is excited by a plane wave with an incidence angle $\theta_s=45^\circ$ in the xz -plane with respect to the metasurface normal plane. The polarisation is taken along the x -axis (TE). To ease fabrication, t is set equal to 100 nm. The behaviour of the structure as a function of remaining parameters was studied by means of FDTD simulations. For $h = 100$ nm and for $w = 0.6 \times p$, when p increases between 200 and 400 nm, the reflectance shows a single peak that redshifts at a rate of about 1.3 nm for every 1 nm increase in period. Besides, this peak reaches an amplitude close to unity when w is between $0.5 \times p$ and $0.7 \times p$. Therefore, we set $w = 0.6 \times p$ to maximise the reflectance.

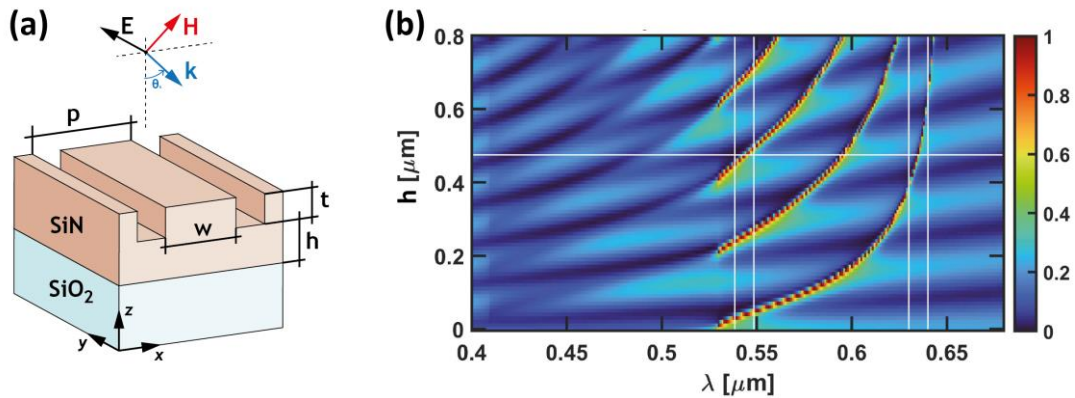


Figure 1. (a) Sketch of the proposed metasurface. (b) Reflectance of the proposed structure as a function of wavelength and waveguide thickness, for $t = 100$ nm, $p = 240$ nm, $w = 0.6 \times p$, for incidence $\theta_s = 45$ and TE polarisation. Vertical white lines delimit a tolerance interval of 10 nm around the wavelengths corresponding to green (543.5 nm) and red (635 nm) colours, while the horizontal white solid line highlights $h = 480$ nm.

Fig. 1(b) shows the reflectance of the proposed structure as a function of h (between 0 and $0.8 \mu\text{m}$) and wavelength when $p = 240 \text{ nm}$ and the remaining parameters chosen as previously reported. For h values below $0.2 \mu\text{m}$, only one reflectivity peak is found, which redshifts as h increases. For an increasing h greater than $0.2 \mu\text{m}$, an increasing number of narrow reflectance peaks arise and redshift, reflecting the presence of an increasing number of guided modes in the structure. For $h = 480 \text{ nm}$ (corresponding to the horizontal white solid line in Fig. 1(b)), two distinct reflectance peaks are observed crossing the 10 nm -wide tolerance regions shown in Fig. 1(b) and located in the vicinity of green (543.5 nm) and red (635 nm), reaching 96% and 99.9% respectively. These two peaks have a linewidth of approximately 3 nm and 1.5 nm , respectively, while the total transparency of the structure, evaluated in the spectral range between 400 and 700 nm , is higher than 83%.

2. CONCLUSIONS

In this contribution we proposed AR near-eye display as a tool to alleviate mild to moderate cognitive impairments by presenting the user with visual information to support of indoor navigation, home safety, communication, and decision-making. We then discussed metasurfaces as an instrument for the development of augmented reality displays for information visualisation. We also proposed the numerical design of a simple transparent metasurface that exploits guided mode resonances to achieve polychromatic selective reflection in green and red. This structure can be valuable for the realisation of visual aids to support individuals with cognitive impairment.

ACKNOWLEDGEMENTS

GM is supported by a grant from Regione Puglia "Research for Innovation" (REFIN). REFIN is an intervention co-financed by the European Union under the POR Puglia 2014-2020, Priority Axis OT X "Investing in education, training and professional training for skills and lifelong learning" - Action 10.4 - DGR 1991/2018 - Notice 2/FSE/2020 n. 57 of 13/05/2019 (BURP n. 52 of 16/06/2019).

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