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Transparent polymer-based metasurfaces for augmented reality display

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Abstract—This work presents the design of transparent polymer-based metasurfaces that achieve selective color reflection through multiple guided mode resonances. This metasurface is promising for augmented reality (AR) applications, such as AR glasses and displays, helping people with cognitive impairments and encouraging active and healthy aging.

Keywords—metasurfaces, guided mode resonances, augmented reality glasses, active and healthy aging

I. INTRODUCTION

Older adults may experience declining quality of life due to age-related impairments in cognitive, physical, psychological, and social abilities. This translates to real-life challenges such as social isolation, loneliness, loss of self-esteem, and difficulties in performing simple activities of daily living, each contributing negatively to their lives [1]. Decision-making is also influenced by declining cognitive abilities, frequently causing others to take over and possibly disregarding personal preferences. Due to all these phenomena, people with cognitive impairments experience a lower life quality, suggesting the need for solutions that promote communication and decision-making for preserving their well-being [2].

In this context, the goal of Augmented Reality (AR) applications for active and healthy aging is to ensure a better quality of life for the elderly or for people with disorders by mitigating and reducing these challenges. Specifically, AR intervention can provide cognitive training to preserve normal daily activities even in advanced age or in presence of disabilities, as well as medical rehabilitation and ultimately facilitate healthcare to improve nutrition, medication management, and health screening [1, 2]. Since it encourages interaction between users, digital informations and physical world, AR has the potential to open up new possibilities for highly engaging human-machine interaction. In fact, AR can integrate the real and digital worlds by superimposing virtual signals, like words or pictures, on the real images thanks to see-through technology [3-6].

This work presents the design of a polymer-based transparent metasurface supporting multiple guided mode

resonances (GMR), which can be exploited for AR glasses and displays. The potential headset architecture consists of a properly angled transparent metalens, which is the subject of the investigation, mounted on a rigid wearable support, resembling a pair of glasses. The system may consist in a directional source, mounted on glasses' temples, which projects the digital image toward the lens at specific wavelength, that then reflects it into the retina. Instead, a possible alternative architecture features the projector near the central region of the headset (the so-called 'bridge'). The key component of the system is represented by the lens, which requires both a high transparency to enable the user to perceive the real world and the ability to reflect certain wavelengths of the visible spectrum to transmit information from the projector to the user. It is worth mentioning that, used at appropriate power levels, signals in the visible spectrum do not cause damage to human eyes. These eye-safe frequencies are suitable for a wide range of applications, from illumination and displaying information to communication [5, 7].

Lenses, mirrors, gratings, and other refractive, reflecting, and diffractive optical elements are used in conjunction to create the majority of the mainstream AR visualization display solutions currently in use [1, 8]. They can be classified into four main categories: conventional optics, holographic optics freeform optics, and waveguide solutions [8]. In solutions leveraging conventional optics, a combination of traditional optical components, such as lenses and mirrors, is used to create off-axis projection systems. A common approach, called birdbath configuration, folds the optical path increasing the system compactness and enabling a broad field of view (FOV) due to its flexible design possibilities [9]. For AR display systems, a typical lens based on holographic optical elements (HOEs) exhibits high sensitivity to both the angle of incidence and wavelength of the illumination light. Chromatic aberration and oblique astigmatism in imaging, as well as material reliability of the constituted HOEs for extended use, are challenges associated with holographic optics solutions [10]. Due to the expanded eyebox, wide FOV and smaller system size, freeform surface (FFS) prisms are frequently utilized in freeform optics solutions. However, for everyday use, the FFS optics components are still relatively thick [11]. The optical waveguide solution is based on a thin planar glass

integrated with in- and out-couplers. This method offers a more compact size, lighter weight, larger eyepiece, as well as appropriate FOV; however, its application for full-color display is limited due to chromatic dispersion caused by light diffraction [12]. These conventional elements are still limited by the underlying physical mechanisms and, therefore, provide limited modulation capability of the light signal and suffer from issues such as bulkiness and significant dispersion. As a result, the current AR visualization systems present a limited FOV, severe chromatic aberration, and large dimensions, reduced perceptual realism and visual discomfort due to the vergence–accommodation conflict [1,8, 13].

In order to increase display performance and compactness in upcoming AR display systems, metasurfaces have the potential to replace the role of traditional optical components [14]. Thanks to their properties, metasurfaces have been receiving a lot of attention since they can be used to manipulate light in multiple ways (phase, amplitude, polarization) over sub-wavelength propagation distances.

AR display systems should be compact, ideally no larger than conventional eyeglasses, to enable comfort and for all-day use [15]. Metasurfaces have been demonstrated to offer higher diffraction efficiency, spectral selectivity, Q-factor, and transmittance than conventional refractive and diffractive optical elements in applications, including AR, virtual reality and wearable devices [15, 16, 17].

Different metasurfaces have been proposed in the literature. For example, metallic structures based on surface plasmons can manipulate light by producing strong light-matter interactions [18, 19]. The negative aspects of this strategy are the intrinsic material losses and that it inevitably increases light absorption [17, 19]. As an alternative technology, dielectric metasurfaces rely on displacement current resonances. Additionally, internal reflection occurs at the interface between low- and high-refractive index materials; as a result, electromagnetic energy is stored as standing waves [18]. As a consequence, all-dielectric metasurfaces are free of ohmic losses and more effective than their metallic counterparts. Moreover, their fabrication method is, in general, compatible with standard processes applied in semiconductor industry. For these reasons, all-dielectric metasurfaces show promise in resolving a number of important technical and physical problems [17, 20, 21].

This work presents a polymer-based transparent metasurface that takes advantage of the benefits of dielectric metasurfaces. This design supports multiple guided mode resonances (GMR) in the visible spectrum, particularly aimed toward AR display applications. The main benefit of employing polymers is that they work well with large-scale manufacturing methods like nanoimprinting. For AR displays that need large and transparent lenses, this scalability is essential.

II. TRANSPARENT POLYMER-BASED METASURFACE

The all-dielectric metasurface proposed in this paper is composed of a transparent metagrating made of polymers. It exploits multiple guided mode resonances to concurrently attain selective reflection of two or more colors in the visible spectrum while transmitting all the others. Optimizing the geometry for simultaneous color selection and concurrently managing multiple guided resonances are the main design challenges.

Figure 1 shows a sketch and outlines the operating principle of the proposed metasurface made of a Hydrex

grating-waveguide system on a Cytop substrate. The diffraction grating on the waveguide acts as a phase adapter between the incident wave and the modes supported by the hydrex core. This enables the excitation of guided modes through direct illumination. The highlighted geometric parameters are the grating period p , the waveguide thickness h , and the grating thickness t .

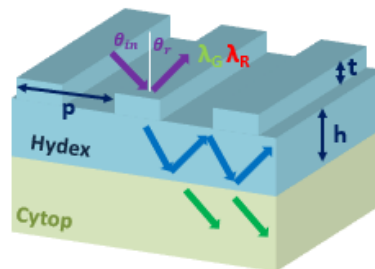


Figure 1: Sketch of the proposed metasurface: waveguide and grating composed of Hydrex on a Cytop substrate. Geometric parameters: p is the grating period, h is the waveguide thickness and t is the grating thickness.

The metasurface structure consists of a Hydrex grating on top of a Hydrex waveguide. This high-index, doped silica glass material offers good transparency and low absorption [22]. The grating-waveguide structure is placed on a Cytop substrate, selected for its high optical transparency and low refractive index (1.34) [23]. Hydrex balances the desirable linear features of silica glass with the nonlinear properties of semiconductors. For this preliminary phase, we set the refractive index to 1.7, as reported in [22].

To achieve selective reflection of two or more colors simultaneously while transmitting all the others, the design requires a large enough index contrast between the substrate and the grating-waveguide system. This condition is necessary to enable the excitation of multiple resonances within the design spectral range, providing the desired color selection. With the proposed configuration, the index contrast is sufficient to excite resonances within the spectral range encompassing the primary green wavelength ($\lambda_G = 542$ nm) and the primary red wavelength ($\lambda_R = 641$ nm).

The grating thickness and the duty cycle are fixed to 100 nm and 60 %, respectively. The optimal values of the grating period and of the waveguide thickness for achieving multi-color selection were determined by solving the grating equation (Eq. (1)) concurrently with the dispersion curves of the guiding structure [5]:

$$N_{eff} = n_i \sin(\theta_{in}) + m \frac{\lambda}{p} \quad (1)$$

where N_{eff} is the effective refractive index of the excited mode, n_i represents the refractive index of the medium through which the incident wave propagates, θ_{in} is the incidence angle, m is the diffraction order, and λ is the wavelength.

III. RESULTS

In this contribute, a preliminary bichromatic configuration (red and green) is designed and analyzed, as it is easier to identify. Future efforts will be devoted to obtaining a trichromatic solution (blue, green and red), which requires studying the structure in a larger geometric parameter space. Numerical simulations were performed through the Rigorous Coupled-Wave Analysis (RCWA) method [24].

Figure 2 shows the reflectance R and transmittance T spectra of the optimal device configuration obtained by parametric

analysis under TM polarization and incidence angle $\theta_{in} = 45^\circ$. Three distinct reflectance peaks (transmittance dips) emerge in the spectrum at about 547 nm, 587 nm, and 636 nm, two of them very close to primary green and red (at 542 nm and 641 nm) identified by the two vertical black lines. This ensures the reflection of vibrant and saturated colors, closely matching the desired color targets.

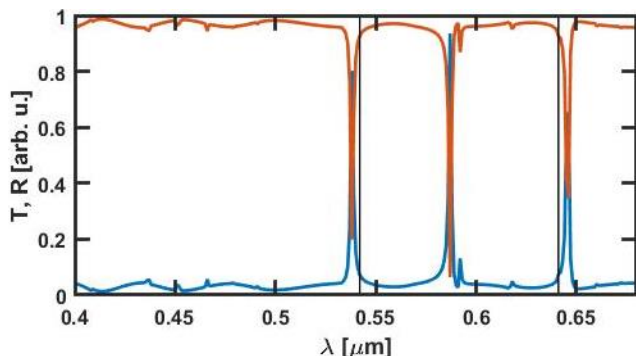


Figure 2: Reflectance (blue curve) and transmittance (red curve) as a function of the wavelength when $p = 0.8425 \mu\text{m}$ and $h = 1.3613 \mu\text{m}$ under TM polarization and incidence angle $\theta_{in} = 45^\circ$. The vertical black lines identify the target wavelengths for the primary green and red (i.e. $\lambda_G = 542 \text{ nm}$ and $\lambda_R = 641 \text{ nm}$, respectively).

Additionally, Fig. 2 shows a high transmittance which ensure high transparency and chromatic neutrality across the rest of the light spectrum, avoiding any distortion of natural color perception in the environment.

The curves displayed in Fig. 2 guarantee that the observer may get primary green and red information while looking through the AR display lenses. Therefore, in principles, it is possible to create user-interactive, instructive overlays by carefully combining these two colors. This expands the range of possible applications for augmented reality displays and may include safety or danger information. For example, green visual-text cues may transmit positive messages, such as permission or safety advice, whereas red cues may represent negative signals, such as limitations or cautions.

IV. CONCLUSIONS

In conclusion, the suggested polymer-based metasurface has potential applications in large-scale augmented reality display systems. This metasurface exploits several guided-mode resonances to enable selective reflection of two or more colors while maintaining excellent transparency for the remaining part of the visible spectrum. This unique ability holds great promise for augmented reality applications, especially for people with cognitive limitations. It is possible to use the capacity to show different colors, like red and green, to provide textual and visual signals that improve home safety, memory, communication, and decision-making.

Furthermore, the use of polymers makes it possible to fabricate vast areas utilizing scalable manufacturing methods like nanoimprinting. It is worth pointing out that since Hydex is a new material, a thorough characterization is required before fabrication, with subsequent design refinement if necessary.

Future efforts will assess the performance of this metalens in terms of other parameters, such as resolution, FOV and eyebox, which are very important in near-eye wearable augmented reality system.

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