

Title	Metasurfaces for sensing and display applications
Authors	Piscopo, Giovanni;Filograno, Francesca;Crouzier, Marius;Vorobev, Artem S.;O'Faolain, Liam;Gauthier-Lafaye, Olivier;Dagens, Béatrice;Calò, Giovanna;Magno, Giovanni
Publication date	2025-08-25
Original Citation	Piscopo, G., Filograno, F., Crouzier, M., Vorobev, A. S., O'Faolain, L., Gauthier-Lafaye, O., Dagens, B., Calò, G. and Magno, G. (2025) 'Metasurfaces for sensing and display applications', 2025 25th Anniversary International Conference on Transparent Optical Networks (ICTON), Barcelona, Spain, 6-10 July 2025, pp. 1-5. https://doi.org/10.1109/ICTON67126.2025.11125261
Type of publication	Conference item;proceedings-article
Link to publisher's version	10.1109/icton67126.2025.11125261
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Download date	2026-10-28 08:09:28
Item downloaded from	https://hdl.handle.net/10468/17902

Metasurfaces for Sensing and Display Applications

Giovanni Piscopo

Munster Technological University, Centre
for Advanced Photonics & Process Analysis
Rossa Avenue, Bishoptown, T12 P928,
Cork Ireland

Polytechnic University of Bari, Department
of Electrical and Information Engineering
Via Edoardo Orabona, 4, 70125, Bari, Italy
giovanni.piscopo@mycit.ie
g.piscopo1@phd.poliba.it

Francesca Filograno

Polytechnic University of Bari, Department
of Electrical and Information Engineering
Via Edoardo Orabona, 4, 70125, Bari, Italy
f.filograno1@phd.poliba.it

Marius Crouzier

C2N, CNRS
Université Paris-Saclay,
Palaiseau, France
marius.crouzier@c2n.upsaclay.fr

Artem S. Vorobev

Munster Technological University, Centre
for Advanced Photonics & Process Analysis
Rossa Avenue, Bishoptown, T12 P928,
Cork Ireland

Tyndall National Institute
Lee Maltings Complex Dyke Parade, T12
R5CP, Cork, Ireland
artem.vorobev@mtu.ie

Liam O'Faolain

Munster Technological University, Centre
for Advanced Photonics & Process Analysis
Rossa Avenue, Bishoptown, T12 P928,
Cork Ireland

Tyndall National Institute
Lee Maltings Complex Dyke Parade, T12
R5CP, Cork, Ireland
william.whelan-curtin@mtu.ie

Olivier Gauthier-Lafaye

LAAS-CNRS
Université de Toulouse, CNRS
Toulouse, France
olivier.gauthier-lafaye@laas.fr

Béatrice Dagens

C2N, CNRS
Université Paris-Saclay,
Palaiseau, France
beatrice.dagens@universite-paris-saclay.fr

Giovanna Calò

Polytechnic University of Bari, Department
of Electrical and Information Engineering
Via Edoardo Orabona, 4, 70125, Bari, Italy
giovanna.calo@poliba.it

Giovanni Magno

Polytechnic University of Bari,
Department of Electrical and Information
Engineering
Via Edoardo Orabona, 4, 70125, Bari,
Italy
giovanni.magno@poliba.it

Abstract—Metasurfaces offer unique capabilities for controlling electromagnetic waves at subwavelength scales, enabling innovative sensing and display applications. In this contribution, we present recent advances in the design and application of functional metasurfaces. Key topics include metasurfaces supporting bound-state-in-the-continuum resonances for enhanced electromagnetic field localization in spectroscopy and guided-mode resonance metasurfaces for polychromatic displays highlighting their potential for multi-color generation. Finally, we explore the design of a thermoplasmonic coupler for localized heat generation to selectively actuate VO₂ phase-change, a critical mechanism for reconfigurable metasurfaces technologies.

Keywords—Metasurfaces, Metalenses, BIC, Thermoplasmonics, Phase-change materials.

I. INTRODUCTION

Originally proposed in 1967 [1], metamaterials have revolutionized materials science, introducing entirely new possibilities for tailoring electromagnetic properties beyond the limits of naturally occurring materials. Metasurfaces are quasi-two-dimensional planar arrays of subwavelength-sized (or sometimes wavelength-scale) structural units called meta-atoms [2], [3]. These units can be arranged in various configurations, including periodic [4], [5], quasi-periodic, or disordered patterns [6]. The geometry, material composition, and spatial organization of meta-atoms directly determine their highly engineerable response [7], enabling the manipulation of fundamental electromagnetic wave properties (amplitude, phase, and polarization) as well as more unusual attributes (angular momentum, topological phases, and orbital properties).

This paradigm enables new functionalities in sensing [8], [9] and display technologies. Recent advances focus on resonant metasurfaces that achieve extreme light confinement or multi-wavelengths operation. In particular, two approaches have garnered intense interest: (i) Bound-state-in-the-continuum (BIC) resonant metasurfaces, for extreme electromagnetic field localization, boosting spectroscopic sensitivity and label-free biosensing, and (ii) guided-mode resonance (GMR) metasurfaces for polychromatic displays, enabling multi-color generation for next-generation augmented reality (AR) devices. Ultra-sensitive detection of biomolecules and environmental analytes can be realized by high-Q BIC resonances that amplify light-matter interactions for spectroscopy and lab-on-chip sensors. Multi-resonant metasurface displays promise lightweight AR glasses with rich color imagery – potentially useful in assistive devices for cognitive support – while maintaining transparency of the real-world view.

In this contribution we discuss three distinct applications of metasurfaces, showcasing how they can offer innovative functionality in compact, scalable platforms ready for next-generation lab-on-chip, biomedical, and visualization applications. Specifically, we discuss advances obtained from the design of polychromatic polymeric metalenses that exploit GMRs selective color reflection, metasurfaces supporting BICs for improved field localization in spectroscopy, and finally the design of a thermoplasmonic coupler enabling localized heat generation for phase-change material control.

II. GMR-BASED METASURFACES FOR AR DISPLAY

Metasurfaces have proven effective in the implementation of AR lenses [7], [8]. In this section, we explore the use of

metasurfaces integrated into AR headset lenses designed to assist patients with cognitive impairments by displaying safety or warning messages, supporting them in performing everyday tasks with increased autonomy [9], [10], [11]. To enhance display performance and compactness in next-generation AR systems, metasurfaces can replace traditional optical components, offering a significantly smaller form factor and overcoming the angular and spectral constraints associated with conventional refractive surfaces [12]. In this work, we introduce a fully polymeric and transparent metalens exploiting multiple guided mode resonances (GMRs) to enable selective color reflection within the visible spectrum. GMR-based metasurfaces are designed using gratings coupled to waveguides. In such structures, resonances arise when the grating's diffractive modes effectively couple to the guided (leaky) modes supported by the grating-waveguide system [13], [14]. In ultrathin waveguides, the supported modes are often limited to the fundamental (zeroth-order) mode, with only a few higher-order diffraction modes possible for TE and TM polarizations [12]. Light can be coupled to these modes via grating diffraction, depending on the angle of incidence and the wavelength. This coupling is engineered using plasmonic or dielectric gratings [15], [16]. Dielectric metasurfaces offer greater optical stability, higher transmission efficiency, simpler, more cost-effective fabrication, and lower optical losses compared to their plasmonic counterparts [17]. Specifically, the proposed design leverages these advantages by employing polymers, that are compatible with scalable fabrication processes such as nanoimprinting. This scalability is crucial for large, transparent lenses in AR visualization systems.

The designed GMR-based metasurface and its working principle are illustrated in Fig. 1. The structure consists of a waveguide and grating made of high-refractive-index AZ5214E unbleached resin placed on a low-refractive-index Cytop substrate known for its outstanding optical transparency. Color selection is achieved through the high contrast between the substrate and grating-waveguide core, allowing simultaneous resonances across the desired spectral range. The proposed configuration provides sufficient refractive index contrast to enable resonances at the primary green (542 nm) and red (641 nm) wavelengths, while transmitting across the remaining part of the spectrum. The key design task is to optimize the geometric parameters of the structure to manage multiple resonances for concurrent color selection. To design a reflective metasurface operating at the primary green and red wavelengths, the waveguide thickness (h) and the grating period (p) (Fig.1) were optimized by simultaneously solving the grating equation [18] and the guiding structure dispersion equations.

Simulations were performed using the RCWA method [19][19]. The grating thickness t and the duty cycle were set to 100 nm and 60 %, respectively. Figure 1 shows the reflectance and transmittance versus wavelength for the optimized parameters $h = 0.45 \mu\text{m}$ and $p = 0.77 \mu\text{m}$ at 45° incidence under TM polarization. The designed configuration exhibits two simultaneous sharp and narrow reflectance (transmittance) peaks (dips) within 15 nm two tolerance windows of centered on the primary green (542 nm) and red (641 nm) wavelengths.

The proposed metasurface can be incorporated into the lens of an AR headset system consisting of a 45° angled lens and a projector fixed to the eyeglass frame. The spectra in Fig.

1 ensure that the observer receives saturated and vibrant green and red colors while looking through the AR display lenses. Additionally, across the rest of the visible spectrum, it exhibits high transmittance, guaranteeing high transparency and chromatic neutrality. By precisely combining only green and red light, user-interactive overlays can be realized: green visual-text cues may convey permission or safety information, while red signals represent prohibitions or alerts.

Future efforts are directed towards the design of a metalens integrated into a more compact and comfortable AR display system. The aim is to achieve a thinner lens profile by eliminating angular placement through a dual-grating configuration. Building on the previously demonstrated simultaneous resonances at the target wavelengths in the reflectance spectrum, the next goal is to deflect the reflected beam toward the user's eye. This will allow the user to comfortably visualize the signals while wearing the AR glasses.

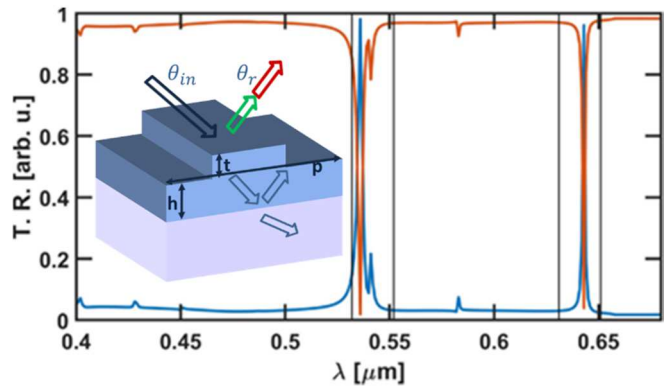


Fig. 1: Inset: unit cell and operating principle of the GMR-based metasurface. An AZ5214E unbleached resin grating-waveguide structure is placed on a Cytop substrate. Geometric parameters: p (grating period), h (waveguide thickness), and t (grating thickness). Reflectance R (blue curve) and transmittance T (red curve) are shown for $p = 0.77 \mu\text{m}$ and $h = 0.45 \mu\text{m}$ under TM polarization at an incidence angle of $\Theta_{in} = 45^\circ$. The vertical black lines identify 15 nm tolerance windows centred on the primary green (542 nm) and red (641 nm) wavelengths.

III. BIC-BASED METASURFACES FOR SENSING AND SPECTROSCOPY

In the field of sensing and spectroscopy, the gold-standard techniques for qualitative and quantitative measurement of molecular presence are Attenuated Total Reflection (ATR) and Surface Enhanced Infrared Absorption Spectroscopy (SEIRAS) [22]. Their key advantage over traditional IR absorption spectroscopy includes the enhancement of light-matter interaction via near-field localization in volumes comparable to the molecule absorption cross section, boosting sensitivity. However, the bulkiness associated with ATR systems as well as metal losses in SEIRAS severely limit their applicability and efficiency.

To overcome these limitations, all-dielectric metasurfaces, [17], particularly those using Bound States in the Continuum (BIC) resonances, provide an efficient and low-loss alternative. BICs are electromagnetic states that exist within the radiative continuum without coupling to it [23]. As non-radiating dark states, they cannot be directly excited by an external source in their pure form. However, by introducing controlled perturbations to the lattice symmetry, these states can be “forced” to radiate a controlled amount of energy. This controlled emission is accompanied by strong near-field localization and enhancement near the periodic lattice, a

consequence of the mode extended lifetime due to minimal losses, making these structures excellent for enhancing light-matter interactions.

In this contribution, we report the numerical design of a silicon-based metasurface consisting of an etched-cross resonator (Fig. 2(a)), whose symmetry is broken by displacing the vertical arm proportionally to an asymmetry parameter d representing the horizontal shift of the vertical arm with respect to the center of the horizontal arm. The resonator is placed on a calcium fluoride (CaF_2) substrate to ensure broad mid-IR transparency, with a 50 nm-thick layer of aluminum dioxide (Al_2O_3) to protect the substrate from etching during fabrication. We then used the 3D Rigorous Coupled-Wave Analysis method (RCWA) to simulate the metasurface under normally incident y -polarized light. Fig. 3 (a) shows simulation results, highlighting the excitation of a sharp Fano resonance (Q-factor up to 8×10^4) in the transmittance spectrum, whose linewidth can be tuned by adjusting the asymmetry parameter d .

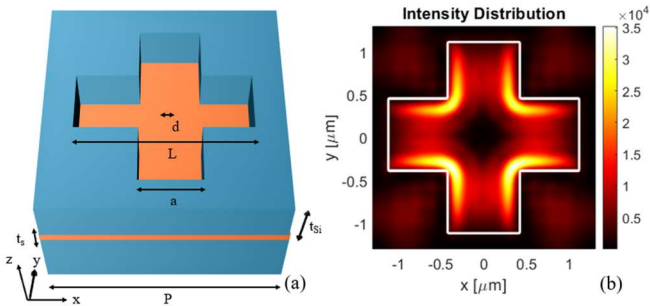


Fig. 2: (a) Sketch of the proposed unit cell. Geometric parameters: $P = 2.6 \mu\text{m}$, $L = 2.22 \mu\text{m}$, $a = 0.84 \mu\text{m}$, $t_{\text{si}} = 0.5 \mu\text{m}$, $t_s = 0.05 \mu\text{m}$. (b) Map of the electric field intensity normalized to the incident wave at $z = 0.25 \mu\text{m}$ for $d = 0.035 \mu\text{m}$, representing the field enhancement. A value exceeding 3×10^4 is primarily localized in the air region of the etched cross.

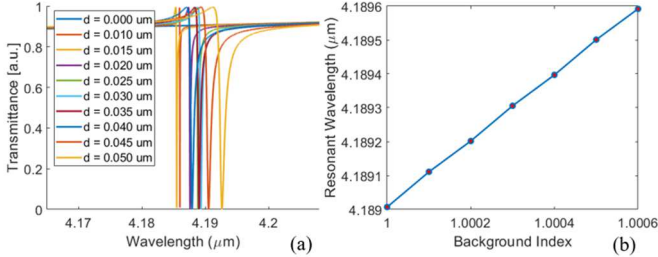


Fig. 3: (a) Transmittance spectra as a function of the asymmetry parameter d , showing the Fano resonance narrowing as d decreases and disappearing at $d = 0 \mu\text{m}$. (b) Resonant wavelength as a function of the medium's refractive index. A sensitivity of 975 nm/RIU is achieved.

Additionally, for $d = 0.035$, we retrieved the field distribution across the structure and computed the field enhancement, defined as the electric field magnitude normalized to the incident field magnitude, as shown in Fig. 2(b). An intensity enhancement exceeding 3×10^4 primarily localized in the air region of the etched cross is observed. Due to this significant field overlap with the surrounding medium, we conducted a sensitivity study by linearly increasing its refractive index from 1 to 1.0006, a range that is compatible with the modification in refractive index induced by the presence of gases. Fig. 3(b) shows the resonant wavelength as a function of the surrounding medium refractive index. By fitting the curve, a remarkable sensitivity of 975 nm/RIU is observed.

IV. THERMOPLASMONIC COUPLER ENABLING VO_2 RECONFIGURATION

Among the different classes of metasurfaces, reconfigurable metasurfaces based on phase-change materials (PCMs) [24], [25] have attracted significant interest. PCMs are well suited to realize dynamically tunable metasurfaces due to their ability to modify their refractive index in response to external stimuli. In particular, VO_2 is notably attractive due to its sub-nanosecond switching time and CMOS compatibility [26]. This transition is accompanied by a significant change in both real and imaginary parts of the refractive index as a function of the temperature and the wavelength [27]. Conventional approaches for triggering the transition usually rely on resistive heating via electrodes or global optical excitation, which may require complex fabrication processes, lack spatial selectivity or require non-integrated free-space excitation schemes [28].

In this section, we propose a novel approach for selectively applying thermal stimuli to induce the VO_2 phase transition at controlled locations in a reconfigurable manner. Our method exploits heating generated by ohmic losses in an integrated plasmonic coupler, enabling optical triggering of the VO_2 phase transition within subwavelength regions. The proposed device, sketched in Fig. 4, consists of a chain of N gold nanoparticles (MNP chain) with elliptical cross section (semi-axes r_x and r_y) and thickness h , arranged linearly with periodicity p , placed at a vertical distance H_{ox} above a silicon-on-insulator (SOI) waveguide, and surrounded by silica (SiO_2). The waveguide, made of silicon (Si) with height H_{wg} , is excited in the near-infrared with the fundamental TE mode that propagates along the x -direction. This mode couples evanescently to the MNP chain over a distance L_{coupling} , leading to the excitation of a propagating, lossy localized surface plasmon (LSP) modes. Due to the very different slopes of the dispersion curves associated with the two coupled structures (see [29] for details), the coupling length exhibits a strong frequency dependence near the localized plasmon resonance. In this regime, ohmic losses are maximized as a result of enhanced modal confinement along the chain. At the coupling length, the TE mode is transferred to the MNP chain, leading to the formation of an intense electromagnetic hotspot, the position of which can be dynamically tuned by varying the excitation frequency. The resulting thermoplasmonic effect enables localized heat generation at the hotspot, which can be conducted to a nearby VO_2 layer, thereby triggering its phase transition.

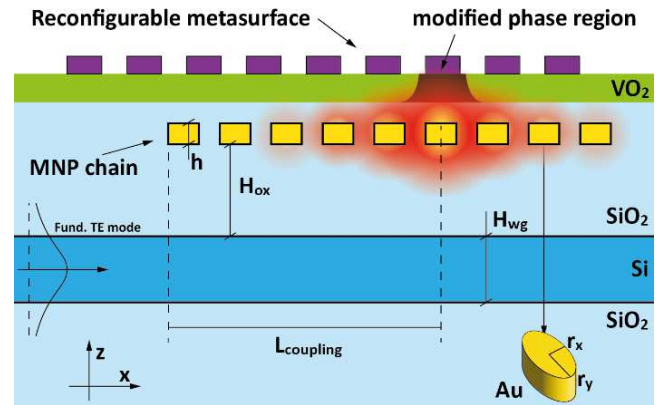


Fig. 4: Schematic representation of the proposed thermoplasmonic architecture for selective phase transition in VO_2 -based reconfigurable metasurfaces. Device components are shown with the geometric variables highlighted.

In an initial phase, we simulated the structure excluding the VO₂ layer while varying the separation distance (H_{ox}) between the plasmonic and dielectric waveguides. The geometric parameters were set as $N = 10$, $H_{ox} = 180$ nm, $H_{wg} = 220$ nm, $W_{wg} = 500$ nm, $p = 150$ nm, $r_x = 42.5$ nm, $r_y = 160$ nm, and $h = 30$ nm. The resulting transmittance map, reported in Fig. 5(a), exhibits a pronounced spectral shift for $H_{ox} < 100$ nm, which is indicative of a strong coupling regime between the two waveguides. For $H_{ox} > 100$ nm, the resonance stabilizes around 1.6 μ m, suggesting a transition to a weak coupling regime. In this regime, we fixed the value of $H_{ox} = 180$ nm, and we analyzed the near-field distribution around the MNP chain as a function of the wavelength shown in Fig. 5 (b). Simulations show a spectral dependence in the position of the localized hotspot, further confirming the wavelength-sensitive nature of the field distribution.

Similarly, a structure with $N = 3$, $H_{ox} = 80$ nm, $H_{wg} = 220$ nm, $W_{wg} = 450$ nm, $r_y = 150$ nm, $r_x = 60$ nm, $p = 180$ nm, and a 100 nm-thick VO₂ layer was simulated using an optical-thermal multiphysics finite-element model. The structure was excited by 0.75 mW optical power at $\lambda = 1480$ nm, for various illumination durations. Figure 6 illustrates the spatial distribution of the transitioned (metallic) VO₂ fraction as a function of exposure time. As expected, the extent of the metallic region increases with longer illumination, confirming the cumulative effect of thermal activation on the insulator-to-metal phase transition.

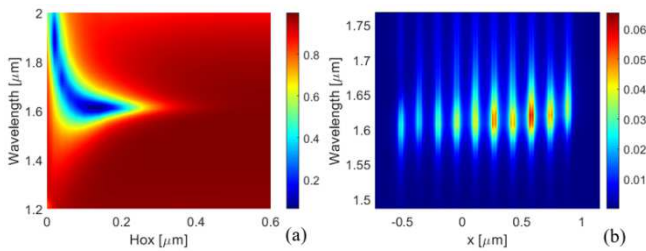


Fig. 5: (a) Transmittance spectrum as a function of the wavelength at the output facet of the SOI waveguide. (b) Hotspot shift along the MNP chain as a function of the wavelength.

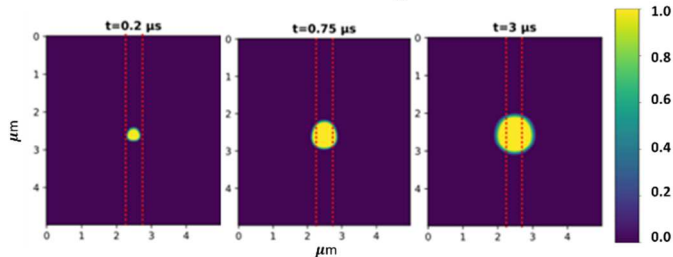


Fig. 6: Transitioned VO₂ amount for different duration times. As expected, the size of the metallic VO₂ spot increases as the duration time increases.

V. CONCLUSION

We presented a set of functional metasurfaces tailored for advanced applications in sensing and display technologies. First, we proposed a polymer-based GMR metasurface capable of dual-wavelength selective reflection in the visible range, designed to enable compact and transparent augmented reality lenses. Next, we explored an all-dielectric metasurface supporting quasi-BIC resonances, achieving extreme near-field localization and demonstrating remarkable sensitivity for mid-IR spectroscopy and refractive index sensing. Finally, we introduced a thermoplasmonic coupling architecture based on

gold nanocylinder chains, capable of selectively inducing localized heating and triggering phase transitions in VO₂, paving the way for dynamically reconfigurable metasurfaces. These architectures exemplify how tailored metasurface designs can address critical challenges in miniaturized photonic systems, providing enhanced field control, high integration compatibility, and versatile spectral responses. These findings open promising avenues for the development of next-generation lab-on-chip platforms, wearable displays, and adaptive optical components.

ACKNOWLEDGMENT

MetaSPECS Project funded by the Research Ireland ID 21/FFP-A/10002.

REFERENCES

- [1] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ϵ and μ ," *Soviet Physics Uspekhi*, vol. 10, no. 4, p. 509, 1968, doi: 10.1070/PU1968v010n04ABEH003699.
- [2] G. Magno, L. Caramia, G. V. Bianco, G. Bruno, A. D'orazio, and M. Grande, "Design of optically transparent metasurfaces based on CVD graphene for mmWave applications," *Sci Rep*, vol. 13, no. 1, 2023, doi: 10.1038/s41598-023-31298-0.
- [3] S. B. Glybovski, S. A. Tretyakov, P. A. Belov, Y. S. Kivshar, and C. R. Simovski, "Metasurfaces: From microwaves to visible," *Phys Rep*, vol. 634, pp. 1–72, 2016, doi: https://doi.org/10.1016/j.physrep.2016.04.004.
- [4] I. Marasco, C. Cantore, G. V. Bianco, G. Bruno, A. D'Orazio, and G. Magno, "Transparent Graphene-Based RIS for 6G Communications in the THz Spectrum," *IEEE Open Journal of Antennas and Propagation*, vol. 6, no. 1, pp. 193–200, 2025, doi: 10.1109/OJAP.2024.3487793.
- [5] I. Marasco, G. Magno, E. Cianca, A. D'Orazio, and M. Grande, "Design of a graphene-based reconfigurable intelligent surface in THz spectrum," in *European Wireless 2023; 28th European Wireless Conference*, 2023, pp. 296–301.
- [6] H. Bertin *et al.*, "Correlated Disordered Plasmonic Nanostructures Arrays for Augmented Reality," *ACS Photonics*, vol. 5, no. 7, pp. 2661–2668, 2018, doi: 10.1021/acsp Photonics.8b00168.
- [7] G. Magno, M. Grande, and A. D'Orazio, "Multifunctional and reconfigurable graphene/liquid crystal-assisted asymmetrical Fabry-Pérot cavity for reflected light control," *Opt Express*, vol. 29, no. 17, pp. 27816–27829, 2021, doi: 10.1364/OE.432166.
- [8] M. L. Tseng, Y. Jahani, A. Leitis, and H. Altug, "Dielectric Metasurfaces Enabling Advanced Optical Biosensors," *ACS Photonics*, vol. 8, no. 1, pp. 47–60, Jan. 2021, doi: 10.1021/acsp Photonics.0c01030.
- [9] S. Zhang *et al.*, "Metasurfaces for biomedical applications: imaging and sensing from a nanophotonics perspective," F. Capasso and D. Couwenberg, Eds., De Gruyter, 2021, pp. 265–300. doi: 10.1515/9783110710687-023.
- [10] S. Zhang *et al.*, "Metasurfaces for biomedical applications: imaging and sensing from a nanophotonics perspective," F. Capasso and D. Couwenberg, Eds., De Gruyter, 2021, pp. 265–300. doi: 10.1515/9783110710687-023.
- [11] G. Piscopo, A. S. Vorobev, G. Magno, and L. O'Faolain, "High-FoM All-Dielectric Metasurface for Advanced Mid-IR Sensing Applications," in *2024 IEEE International Humanitarian Technologies Conference (IHTC)*, 2024, pp. 1–6. doi: 10.1109/IHTC61819.2024.10855116.
- [12] R. S. Baragash, H. Aldowah, and S. Ghazal, "Virtual and augmented reality applications to improve older adults' quality of life: A systematic mapping review and future directions," *Digit Health*, vol. 8, p. 20552076221132100, Jan. 2022, doi: 10.1177/20552076221132099.
- [13] G. Magno, B. Dagens, A. D'Orazio, and O. Gauthier-Lafaye, "Multi-colour reflective metagrating with neutral transparency for augmented reality," *Opt Express*, vol. 32, no. 15, pp. 25545–25559, 2024, doi: 10.1364/OE.520430.
- [14] F. Filograno *et al.*, "Transparent polymer-based metasurfaces for augmented reality display," in *ICOP 2024 Italian Conference on optics and Photonics*, Firenze, Italy, Jun. 2024. doi: 10.1364/oe.520430.

- [15] Y. Li *et al.*, “Ultracompact multifunctional metalens visor for augmented reality displays,” *PhotonIX*, vol. 3, no. 1, p. 29, 2022, doi: 10.1186/s43074-022-00075-z.
- [16] G. Quaranta, G. Basset, O. J. F. Martin, and B. Gallinet, “Recent Advances in Resonant Waveguide Gratings,” *Laser Photon Rev*, vol. 12, no. 9, p. 1800017, Sep. 2018, doi: <https://doi.org/10.1002/lpor.201800017>.
- [17] F. Filograno *et al.*, “Guided Mode Resonant Metagrating for Augmented Reality Lenses and Biosensing,” in *2024 IEEE International Humanitarian Technologies Conference (IHTC)*, 2024, pp. 1–6, doi: 10.1109/IHTC61819.2024.10855055.
- [18] G. Magno *et al.*, “Mesoscopic self-collimation along arbitrary directions and below the light line,” *Opt Express*, vol. 27, no. 21, pp. 30287–30296, 2019, doi: 10.1364/OE.27.030287.
- [19] L. Collard *et al.*, “Holographic Manipulation of Nanostructured Fiber Optics Enables Spatially-Resolved, Reconfigurable Optical Control of Plasmonic Local Field Enhancement and SERS,” *Small*, vol. 18, no. 23, p. 2200975, Jun. 2022, doi: <https://doi.org/10.1002/smll.202200975>.
- [20] J. Wang and J. Du, “Plasmonic and Dielectric Metasurfaces: Design, Fabrication and Applications,” *Applied Sciences*, vol. 6, no. 9, 2016, doi: 10.3390/app6090239.
- [21] J.-P. Hugonin and P. Lalanne, “Light-in-complex-nanostructures/RETICOLO: V9,” Jan. 2021, doi: 10.5281/ZENODO.5905381.
- [22] H.-L. Wang, E.-M. You, R. Panneerselvam, S.-Y. Ding, and Z.-Q. Tian, “Advances of surface-enhanced Raman and IR spectroscopies: from nano/microstructures to macro-optical design,” *Light Sci Appl*, vol. 10, no. 1, p. 161, 2021, doi: 10.1038/s41377-021-00599-2.
- [23] M. Zhou *et al.*, “Selective perturbation of eigenfield enables high-Q quasi-bound states in the continuum in dielectric metasurfaces,” *ACS Photonics*, vol. 11, no. 6, pp. 2413–2421, 2024, doi: 10.1021/acsp Photonics.4c00319.
- [24] L. Liu, L. Kang, T. S. Mayer, and D. H. Werner, “Hybrid metamaterials for electrically triggered multifunctional control,” *Nat Commun*, vol. 7, no. 1, p. 13236, 2016, doi: 10.1038/ncomms13236.
- [25] F.-Z. Shu *et al.*, “Electrically driven tunable broadband polarization states via active metasurfaces based on joule-heat-induced phase transition of vanadium dioxide,” *Laser Photon Rev*, vol. 15, no. 10, p. 2100155, 2021, doi: 10.1002/lpor.202100155.
- [26] G. Baffou and R. Quidant, “Thermo-plasmonics: using metallic nanostructures as nano-sources of heat,” *Laser Photon Rev*, vol. 7, no. 2, pp. 171–187, 2013, doi: 10.1002/lpor.201200003.
- [27] T. Guo *et al.*, “Durable and programmable ultrafast nanophotonic matrix of spectral pixels,” *Nat Nanotechnol*, vol. 19, no. 11, pp. 1635–1643, 2024, doi: 10.1038/s41565-024-01756-5.
- [28] Q. Song, M. Odeh, J. Zúñiga-Pérez, B. Kanté, and P. Genevet, “Plasmonic topological metasurface by encircling an exceptional point,” *Science*, vol. 373, no. 6559, pp. 1133–1137, 2021, doi: 10.1126/science.abj3179.
- [29] G. Magno *et al.*, “Strong coupling and vortexes assisted slow light in plasmonic chain-SOI waveguide systems,” *Sci Rep*, vol. 7, no. 1, 2017, doi: 10.1038/s41598-017-07700-z.