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Robust Topological Scattering and Radiating Structures: Bridging Free-Space Propagation and Surface Waves on Complex Objects

**Francesco Monticone
CORNELL UNIVERSITY
341 PINE TREE RD
ITHACA, NY, 14850
USA**

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14. ABSTRACT In the second year of this project, my research group focused on two main areas of interest: (1) Topological and nonreciprocal electromagnetics in plasmas and plasmonic media; (2) Local and nonlocal metasurfaces. In the following, I discuss our main research accomplishments and results. (1) Topological and nonreciprocal electromagnetics in plasmas and plasmonic media. a. We investigated the implications of causality for nonreciprocal plasma media, such as the existence of a low-loss frequency window with anomalous nonmonotonic dispersion, which enables a giant and broadband nonreciprocal response. This is in stark contrast with conventional nongyrotropic passive materials, for which the frequency derivative of the permittivity dispersion function is always positive in low-loss regions. These findings may pave the way for superior nonreciprocal components in terms of bandwidth of operation and compactness, with orders-of-magnitude reductions in size. b. We theoretically demonstrated extreme field enhancements and giant broadband nonlinear effects in nonreciprocal waveguides with one-way modes. Specifically, we showed that remarkably strong field hot spots can be achieved when the unidirectional waveguiding structure is terminated with a suitable boundary that fully stops the one-way mode. Such a large field enhancement, originating from a non-resonant effect, is fundamentally different from the narrow-band field concentration effects in resonant plasmonic structures. We showed that this effect can lead to a substantial boosting of nonlinear light-matter interactions, exemplified by an improvement of several orders of magnitude in the third-harmonic-generation efficiency, which is of large significance for several applications. More broadly, our findings show the potential of extreme nonreciprocal configurations for enhanced wave-matter interactions.					
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AFOSR Grant # FA9550-19-1-0043

Principal Investigator: **Prof. Francesco Monticone**, School of Electrical and Computer Engineering, Cornell University, Ithaca, NY, USA.

Program Officer: **Dr. Arje Nachman**

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Research accomplishments and key results

In the second year of this project, my research group focused on two main areas of interest: (1) Topological and nonreciprocal electromagnetics in plasmas and plasmonic media; (2) Local and nonlocal metasurfaces. In the following, I discuss our main research accomplishments and results.

(1) Topological and nonreciprocal electromagnetics in plasmas and plasmonic media.

a. We investigated the implications of causality for nonreciprocal plasma media, such as the existence of a low-loss frequency window with anomalous nonmonotonic dispersion, which enables a giant and broadband nonreciprocal response (Fig. 1). This is in stark contrast with conventional nongyrotropic passive materials, for which the frequency derivative of the permittivity dispersion function is always positive in low-loss regions. These findings may pave the way for superior nonreciprocal components in terms of bandwidth of operation and compactness, with orders-of-magnitude reductions in size.

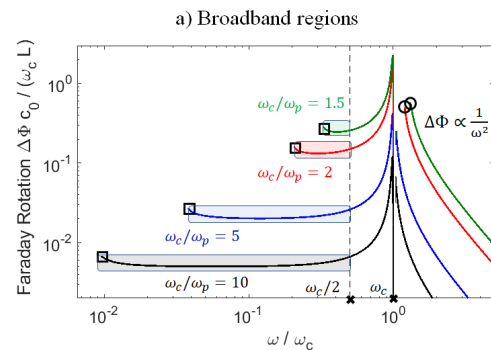


Fig. 1. Broadband regions of dispersionless Faraday rotation (shaded areas). From Ref. [11] in the list below.

b. We theoretically demonstrated extreme field enhancements and giant broadband nonlinear effects in nonreciprocal waveguides with one-way modes. Specifically, we showed that remarkably strong field hot spots can be achieved when the unidirectional waveguiding structure is terminated with a suitable boundary that fully stops the one-way mode (Fig. 2). Such a large field enhancement, originating from a nonresonant effect, is fundamentally different from the narrow-band field concentration effects in resonant plasmonic structures. We showed that this effect can lead to a substantial boosting of nonlinear light-matter interactions, exemplified by an improvement of several orders of magnitude in the third-harmonic-generation efficiency, which is of large significance for several applications. More broadly, our findings show the potential of extreme nonreciprocal configurations for enhanced wave-matter interactions.

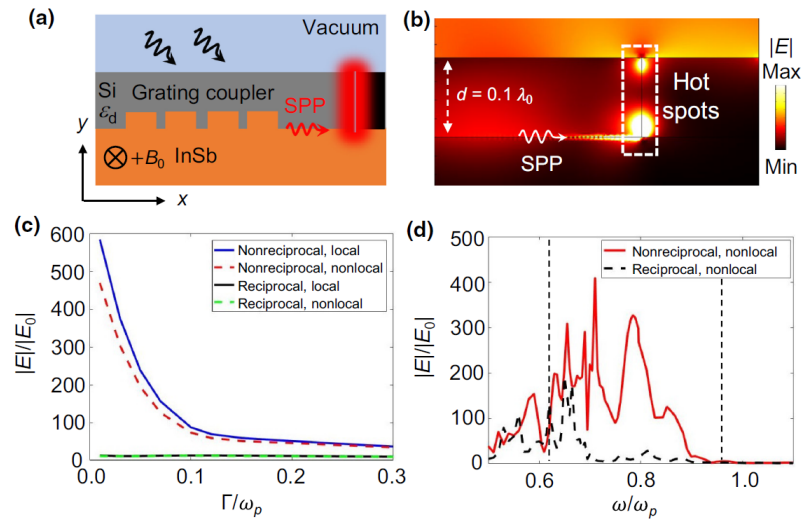


Fig. 2 Broadband field enhancement and giant field hot spots in terminated one-way waveguides. (a) Geometry under consideration and (b) distribution of the electric field magnitude, with intense field hot spots. (c) Field enhancement at the termination for different scenarios (reciprocal or nonreciprocal and local or nonlocal) as a function of the damping rate. (d) Field enhancement as a function of frequency. From Ref. [12] in the list below.

- c. We rigorously studied the impact of dissipation in topological electromagnetics, focusing on two main problems:
- i. We theoretically demonstrated two general classes of apparent violations of the bulk-edge correspondence principle for continuous topological electromagnetic materials, associated with the asymptotic behavior of the surface modes for diverging wavenumbers (Fig. 3). Considering a nonreciprocal plasma as a model system, we showed that the inclusion of spatial dispersion formally restores the bulk-edge correspondence by avoiding an unphysical response at large wavenumbers. Most importantly, however, our findings demonstrated that, for the considered cases, the correspondence principle is physically violated for all practical purposes, as a result of the unavoidable attenuation of highly confined modes even if all materials are assumed perfect, with zero intrinsic bulk losses, due to confinement-induced Landau damping or nonlocality-induced radiation leakage. Our work helps clarifying the subtle and rich topological wave physics of continuous media.
 - ii. We investigated the robustness of topological Weyl (meta)materials in the presence of dissipation. In particular, we demonstrated that the symmetry properties of the topological material play a crucial role in the annihilation of topological charges in the presence of losses. We considered the specific example of a continuous plasma medium and compared two possible realizations of a Weyl-point topological dispersion based on breaking time-reversal symmetry (reciprocity) or breaking inversion symmetry. We proved that the topological state is fundamentally more robust against losses in the nonreciprocal realization (Fig. 4). Our findings elucidate the impact of dissipation on three-dimensional topological materials and metamaterials.

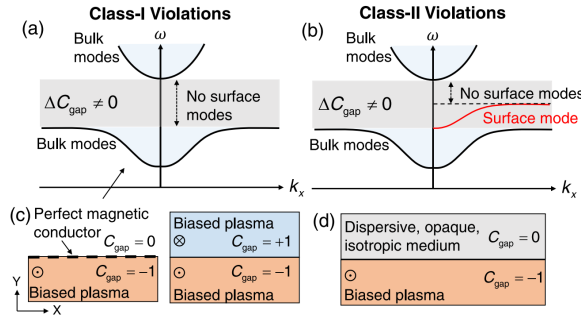


Fig. 3. Physical violations of the bulk-edge correspondence in topological electromagnetics. (a),(b) Illustration of the typical dispersion diagram for the two classes of violations we considered in [16]. (c) Configurations that exhibit class-I violations of the bulk-edge correspondence. (d) Configuration that implements a class-II violation. From Ref. [16] in the list below.

- d. As an alternative to the use of an external magnetic bias (or complicated space-time modulations), we started investigating the possibility of breaking reciprocity in conducting materials using a direct-current bias. The resulting Doppler shift experienced by the electromagnetic modes makes the dispersion diagram asymmetric and unidirectional (Fig. 5). We also studied the presence of inflexion points and exceptional points in the dispersion relation of surface plasmon-polariton modes, and the implication of unidirectionality for nonreciprocal thermal radiation effects.

(2) Local and nonlocal metasurfaces.

- a. We discovered the presence of exceptional points in the electromagnetic response of non-Hermitian metasurfaces supporting unidirectional line waves (Fig. 6). Interestingly, we showed that the “phase transition” at an exceptional point may provide a unified description of the different classes of unidirectional line waves recently studied in the literature. Our results could have important implications for exceptional-point-based sensing on a planar platform.

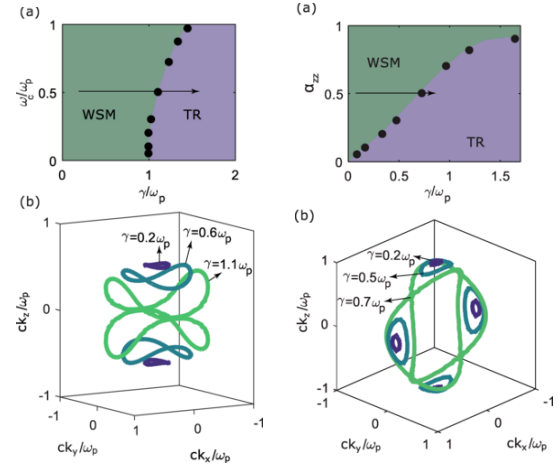


Fig. 4. Impact of dissipation on 3D topological metamaterials. Top panels: Topological phases of a magnetized plasma (left) and a chiral plasma metamaterial (right). Bottom panels: Rings of exceptional points for different values of dissipation. When rings with opposite topological charge come into contact, the material becomes topologically trivial. From Ref. [15] in the list below.

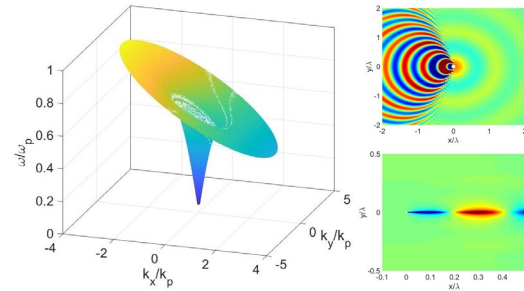


Fig. 5. Current-based nonreciprocity. Asymmetric, nonreciprocal dispersion diagram for the surface modes of a current-biased plasmonic material (left), and examples of unidirectional surface wave propagation at two different frequencies (right). From Ref. [5] in the list below.

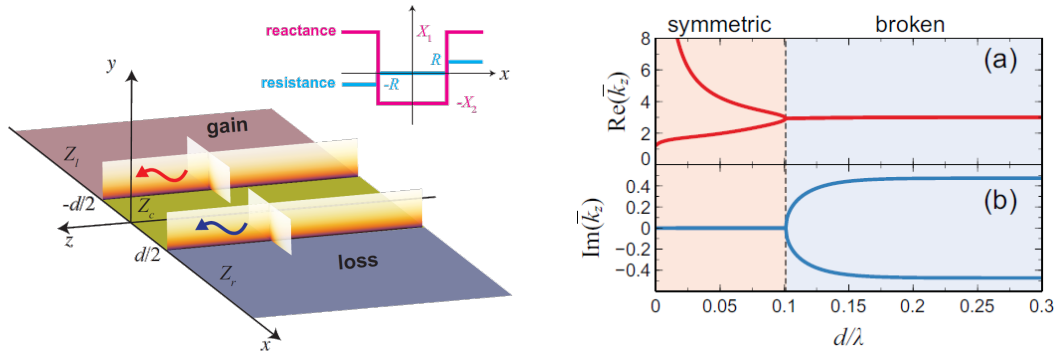


Fig. 6. Exceptional points on metasurfaces. Left: Problem geometry: a non-Hermitian metasurface with a discontinuous profile of its surface resistance and reactance. The two interfaces/discontinuities support coupled line waves. Right: Eigenmode analysis, showing the real and imaginary part of the mode index, as a function of distance between the metasurface junctions. An exceptional point (square-root branch point) marks the bifurcation of the eigensolutions. From Ref. [6] in the list below.

- b. We derived fundamental bandwidth limits that apply to dispersion-engineered metalenses regardless of their implementation. Specifically, we recognized that the product between achievable time delay and bandwidth is limited in any time-invariant linear system, and we applied well-established bounds on this product to a metalens focusing system (Fig. 7). We then showed that all dispersion engineered metalenses designed thus far obey the appropriate bandwidth limit. The derived physical bounds provide a useful metric to compare and assess the performance of different devices, and they offer fundamental insight into how to design superior broadband metalenses. We also identified potential directions to approach and bypass these bounds. Several research groups have been taking inspiration from our results to design better metalenses and assess their theoretical limits.

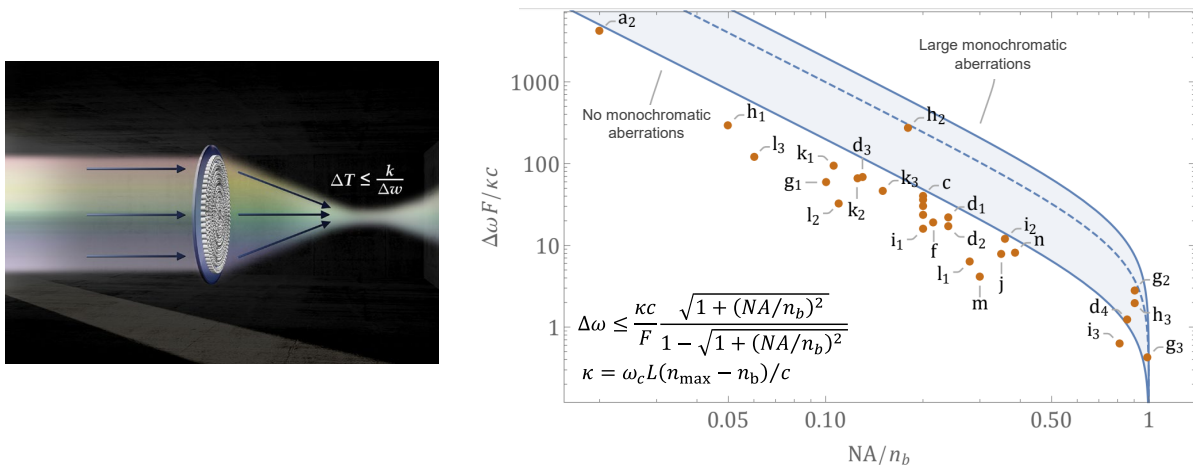


Fig. 7. Physical bounds on dispersion-engineered metalenses. Left: Illustration of a dispersion-engineered achromatic metalens and the delay-bandwidth product. Right: Comparison of published achromatic metalens designs against the derived bandwidth limits. Each data point in the plot represents a single design. The performance of each metalens is represented in terms of numerical aperture and bandwidth. In order to compare vastly different designs against the bandwidth bounds, the bandwidths are suitably normalized. From Ref. [14] in the list below.

c. In 2020, we also investigated nonlocal metasurfaces for “space compression” (Fig. 8), which may have great potential to miniaturize optical systems for focusing and imaging, microwave/millimeter-wave lens antennas, etc. We first derived a fundamental trade-off between the length of compressed free space and the operating angular range, which explains some of the limitations of earlier designs, and we then proposed a solution to relax this trade-off using nonlocal metasurface structures composed of suitably coupled resonant layers. This strategy, inspired by coupled-resonator-based pass-band microwave filters, allows replacing free-space volumes of arbitrary length over wide angular ranges, and with high transmittance. Finally, we theoretically demonstrated, for the first time, the potential of combining local and nonlocal metasurfaces to realize compact, fully solid-state, planar structures for focusing, imaging, and magnification, in which the focal length of the lens (and hence its magnifying power) does not dictate the actual distance at which focusing is achieved. Our findings are expected to extend the reach of the field of metasurfaces and open new unexplored opportunities. Following suggestions from PO Nachman, we are also investigating how to apply these ideas to realize superior, lightweight, and compact optics for telescopes and rifle scopes.

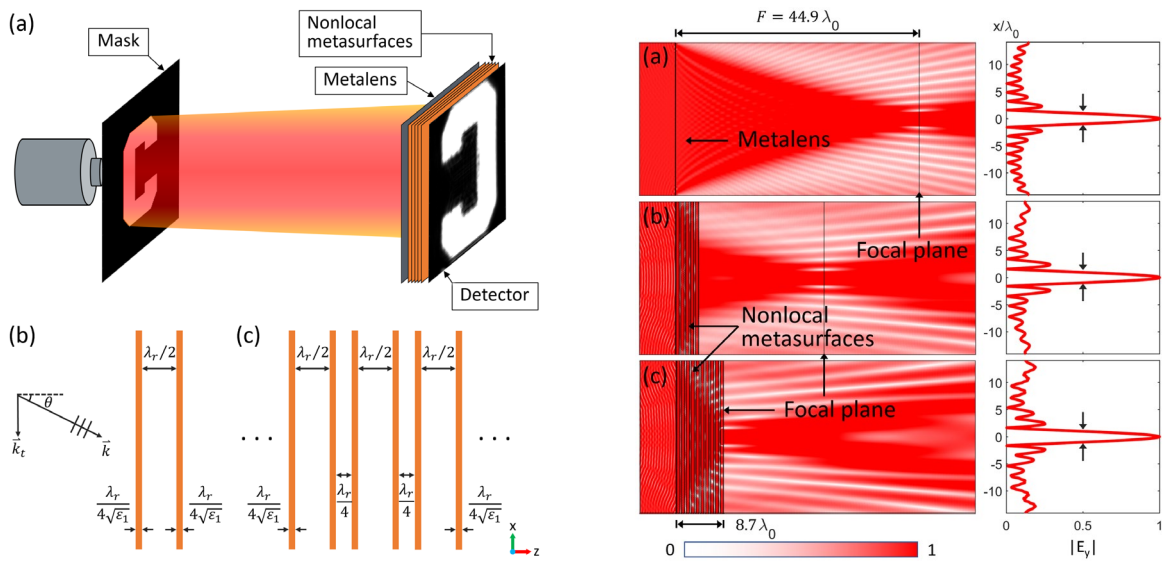


Fig. 8. Nonlocal metasurfaces for space compression. Left: (a) Illustration of a truly solid-state flat-optics imaging system, in which nonlocal metasurfaces replace and compress the entire free-space volume between a flat metalens and the detector on the observation plane, hence miniaturizing the entire optical system without affecting the imaging performance. (b,c) Planar dielectric structures supporting guided-mode resonances that implement the required nonlocal response. Right: Field amplitude distribution for a plane wave incident on (a) a local idealized metalens, and (b,c) the same metalens followed by nonlocal metasurfaces with 5 layers (panel b) and 10 layers (panel c). The dielectric nonlocal structure moves the focal plane closer and closer to the metalens, with minimal distortions and without changing the focal length of the metalens (which is a property of the local metalens itself). In panel (c), all space between the lens and the focal plane has been replaced and compressed by the nonlocal structure, realizing a compact, solid-state, flat-optics device. From Ref. [1] in the list below.

- d. Finally, following suggestions from PO Nachman, we started investigating active nonlocal metasurfaces for broadband omnidirectional energy tunneling through opaque media, with particular focus on the problem of communications through plasma sheaths around hypersonic vehicles. As part of our preliminary work, we derived closed-form formulas for the tunneling condition, and we determined what issues need to be addressed to make this tunneling effect sufficiently broadband to be of practical use for GPS signals. Further investigations are currently underway.

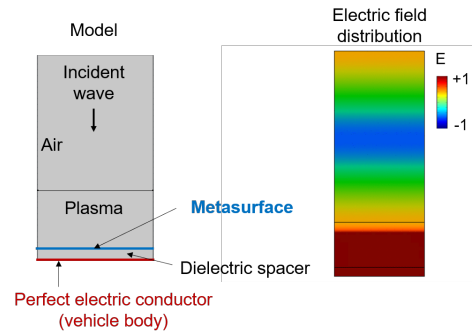


Fig. 9. Metasurfaces for broadband energy tunneling through plasma sheaths.

Our work on this project in 2020 has led to 9 publications in top tier journals, 3 accepted papers, and 7 papers currently under review. This grant has also supported 15 conference papers and talks (many of these are *invited talks* at top tier conferences in electromagnetics, photonics, and applied mathematics). A full list of these journal publications and conference papers and talks is provided in the following.

List of publications supported by this grant (2020):

SUBMITTED:

1. A. Chen, and **F. Monticone**, “Truly solid-state flat optics with dielectric nonlocal metasurfaces,” under review.
2. Z. Hayran, and **F. Monticone**, “Spectral Causality and the Scattering of Waves,” under review.
3. K. Shastri, M. I. Abdelrahman, and **F. Monticone**, “Nonreciprocal and topological plasmonics,” under review (invited review paper).
4. K. Shastri, and **F. Monticone**, “Fundamental tradeoff between absorptivity and omnidirectionality in thin metasurface-based absorbers and emitters” under review.
5. S. A. H. Gangaraj, and **F. Monticone**, “Drifting Electrons: Nonreciprocal Plasmonics and Thermal Photonics” under review.
6. M. Moccia, G. Castaldi, **F. Monticone***, and V. Galdi*, “Exceptional Points in the Flatland: A Non-Hermitian Line-Wave Scenario,” under review. *Co-corresponding authors.
7. F. B. Arango, F. Alpegiani, D. Conteduca, A. Opheij, A. Chen, T. Krauss, A. Alù, **F. Monticone***, and L. Kuipers*, “Cloaked Near-Field Probe for Non-Invasive Near-Field Optical Microscopy,” under review. * Co-corresponding authors.

ACCEPTED:

8. Z. Hayran, and **F. Monticone**, “Capturing Broadband Light in a Compact Bound State in the Continuum,” ACS Photonics, in press.
9. M. I. Abdelrahman, Z. Hayran, A. Chen, and **F. Monticone**, “Can Fast-Light Cloaks Achieve True Broadband Invisibility?” Nature Communications, in press.
10. J. B. Khurgin, K. Shastri, U. Levy, and **F. Monticone**, “Emulating Exceptional-Point Encirclements Using Imperfect (Leaky) Photonic Components,” Optica, in press.

PUBLISHED:

11. M. I. Abdelrahman, and **F. Monticone**, “Broadband and Giant Nonreciprocity at the Subwavelength Scale in Magneto-Plasmonic Materials,” Physical Review B, vol. 102, no. 15, p. 155420, Oct. 2020. doi: 10.1103/PhysRevB.102.155420
12. S. A. H. Gangaraj, B. Jin, C. Argyropoulos, and **F. Monticone**, “Broadband Field Enhancement and Giant Nonlinear Effects in Terminated Unidirectional Plasmonic Waveguides,” Physical Review Applied, vol. 14, no. 5, p. 054061, Nov. 2020. doi: 10.1103/PhysRevApplied.14.054061
13. **F. Monticone**, “A Truly One-Way Lane for Surface Plasmon-Polaritons,” Nature Photonics, vol. 14, pp. 461-465, July 2020. (invited Commentary Article) [**Featured on the journal cover**; Highlighted on Cornell Engineering News] doi: 10.1038/s41566-020-0662-5
14. F. Presutti, and **F. Monticone**, “Focusing on Bandwidth: Achromatic Metalens Limits,” Optica, vol. 7, no. 6, pp. 624-631, June 2020. [Highlighted on Cornell Engineering News] doi: 10.1364/OPTICA.389404
15. K. Shastri, and **F. Monticone**, “Dissipation-Induced Topological Transitions in Weyl Semi-Metals,” Physical Review Research, vol. 2, no. 3, p.033065, July 2020. doi: 10.1103/PhysRevResearch.2.033065
16. S. A. H. Gangaraj, and **F. Monticone**, “Physical Violations of the Bulk-Edge Correspondence in Topological Electromagnetics,” Physical Review Letters, vol. 124, no. 15, p. 153901, April 2020. doi: 10.1103/PhysRevLett.124.153901
17. S. A. H. Gangaraj, C. Valagiannopoulos, and **F. Monticone**, “Topological Scattering Resonances at Ultra-Low Frequencies,” Physical Review Research, vol. 2, no. 2, p. 023180, May 2020. doi: 10.1103/PhysRevResearch.2.023180
18. S. Pakniyat, A. M. Holmes, G. W. Hanson, S. A. Hassani Gangaraj, M. Antezza, M. G. Silveirinha, S. Jam and **F. Monticone**, “Non-Reciprocal, Robust Surface Plasmon Polaritons on Gyrotropic Interfaces,” IEEE Transaction on Antenna and Propagation, vol. 68, no. 5, May 2020. doi: 10.1109/TAP.2020.2969725

19. A. Chen, and **F. Monticone**, “Active Scattering-Cancellation Cloaking: Broadband Invisibility and Stability Constraints,” IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, March 2020. (invited special issue paper) doi: 10.1109/TAP.2019.2948528

Conference papers and talks supported by this grant (2020):

INVITED:

1. **F. Monticone**, “New Frontiers for Electromagnetic Wave Manipulation Using Metamaterials, Metasurfaces and Nanostructures,” 2020 IEEE Rochester Section Joint Chapters Meeting, Online, October 27, 2020. (*invited talk*)
2. **F. Monticone**, “Focusing on Bandwidth: Fundamental Limits to Broadband Metalensing and Scattering Engineering,” Metamaterials’2020, Online, September 28 - October 3, 2020. (*invited talk*)
3. **F. Monticone**, “Beyond Conventional Physical Bounds with Spacetime Metamaterials,” SPIE Optics and Photonics 2020, Online, August 23-27, 2020. (*invited talk*)
4. **F. Monticone**, “Focusing on Bandwidth: Fundamental Limits to Broadband Metalensing and Scattering Engineering,” SPIE Optics and Photonics 2020, Online, August 23-27, 2020. (*invited talk*)
5. **F. Monticone**, “New Frontiers for Metasurfaces: From Ultra-Broadband Metalenses to Nonlocal Meta-Optics,” Nanophotonics guest-speaker webinar series at Corning Inc., Online, August 14, 2020. (*invited webinar*)
6. **F. Monticone**, “Controlling Light with Metasurfaces: New Frontiers and Fundamental Limits,” Plasmonica 2020 - International Workshop on Plasmonics, Online, April 30, 2020. (*invited talk*)

CONTRIBUTED:

7. S. A. H. Gangaraj, B. Jin, C. Argyropoulos, and **F. Monticone**, “Broadband Enhanced Nonlinear Harmonic Generation in Terminated Unidirectional Plasmonic Waveguides,” Metamaterials’2020, Online, September 28 - October 3, 2020.
8. K. Shastri, and **F. Monticone**, “Omnidirectional, Frequency Selective Metasurface Absorber based on Quasi-Bound States in the Continuum,” Metamaterials’ 2020, Online, September 28 - October 3, 2020.
9. A. Chen, and **F. Monticone**, “Broadband Absorption Limits for Ultrathin Solar Cells,” Metamaterials’2020, Online, September 28 - October 3, 2020.
10. M. I. Abdelrahman, and **F. Monticone**, “Towards Broadband and Compact Giant Nonreciprocity at THz Frequencies,” Metamaterials’2020, Online, September 28 - October 3, 2020.

11. Z. Hayran, and **F. Monticone**, “Temporally Modulated Non-Hermitian Optical Systems Based on Epsilon-Near-Zero Media,” *Metamaterials’2020*, Online, September 28 - October 3, 2020. [Third Prize of the Student Paper Competition]
12. S. A. H. Gangaraj, and **F. Monticone**, “Violations of the Bulk-Edge Correspondence in Topological Electromagnetics,” *2020 IEEE International Symposium on Antennas and Propagation (AP-S/URSI 2020)*, Online, July 5-10, 2020.
13. S. A. H. Gangaraj, and **F. Monticone**, “Violations of the Bulk-Edge Correspondence for Uniform Topological Photonic Materials,” *Conference on Laser and Electro- Optics (CLEO)*, Online, May 10-15, 2020.
14. K. Shastri, and **F. Monticone**, “Dissipation of Topological Charge in Plasmonic Weyl Semimetals,” *Conference on Laser and Electro-Optics (CLEO)*, Online, May 10-15, 2020.
15. F. Presutti, and **F. Monticone**, “Focusing on Bandwidth: Achromatic Metalens Limits,” *Conference on Laser and Electro-Optics (CLEO)*, Online, May 10-15, 2020.