Thursday, July 25TH

Perspectives and Next Generation Metasurfaces

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09:55 - 10:20	Alfredo De Rossi	All-optical photonic reservoir computing: harnessing complexity in nonlinear photonics
10:20 - 10:50	Coffee Break	
Session II		
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11:15 - 11:40	Andrea Di Falco	Material platforms for biophotonic applications of holographic metasurfaces
11:40 - 12:05	Ivano Alessandri	Metasurfaces for enhanced Raman scattering and photocatalysis
12:05 - 14:00	Lunch Break	
Session III		
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14:25 - 14:50	Riccardo Sapienza	Temporal diffraction and synthetic motion from time-varying metamaterials
14:50 - 15:35	Vladimir Shalaev	Extreme Space-Time Optics & Quantum Meta-Photonics
Session IV		
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15:50 - 16:05	Rachel Won	Facts and Trends in Photonics Publishing
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Advancing Nanophotonics: From Tailorable Materials to Novel Phenomena

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Abstract

The recent advent of tailorable photonic materials such as plasmonic ceramics including transition metal nitrides (TMNs), MXenes, Weyl semimetals and transparent conducting oxides (TCOs) is currently driving the development of new concepts and devices for IT, communication, sustainable energy and quantum technologies. In addition to great tailorability of their optical properties, strong plasmonic behavior, optical nonlinearities, these materials offer pathways to uncovering new optical and quantum phenomena ranging from epsilon-near-zero behavior to transdimensional photonics and strongly correlated systems. In this talk, we explore novel applications of TMNs (titanium nitride, zirconium nitride) and TCOs for flat optics, all-optical switching, high-harmonic-based XUV generation as well as for demonstrating new physical effects in atomically thin, transdimensional plasmonic films related to strong light confinement and metal-to-insulator transition. Our work paves the way to novel phenomena and device design with ultrafast tunable and tailorable optical materials.

Metamaterial quantum cascade emitter at 9µm

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Abstract

Patch-antenna metamaterials have been largely used for the development of optoelectronic devices in the mid-infrared and THz range [1-4]. The design of the metamaterial is an extra degree of freedom to improve device performances. The optimal configuration depends on the device functionality and can be reached by tuning its geometrical parameters: the key condition for detectors/modulators is the critical coupling [5], whereas for lasers the fundamental issue is to minimise the optical losses.

In this work, we present a quantum cascade emitter at 9µm in InGaAs/AlInAs based on a patch antenna array, acting as metamaterial. The light-matter interaction is enhanced by the microcavity effect, induced by the field confinement between top and ground metals. The patch-antenna couples the radiation with the free space and the emitted light is converted in surface-emitting direction (dipole flipping). The emission is spectrally filtered, as the electroluminescence spectral components detuned from the cavity mode are suppressed. Also, the array configuration helps the directivity because all the antennas interact constructively along one direction and destructively in the remaining space, resulting in a narrow radiation pattern, as it showed in the main panel of Figure 1.

Moreover, the configuration of sparse patches forming "diluted" arrays is advantageous in terms of low threshold currents and better thermal dissipation. Finally, the possibility of rearranging and singularly addressing the elements also offers new perspectives for phased array lasers for wavefront engineering of the beam.

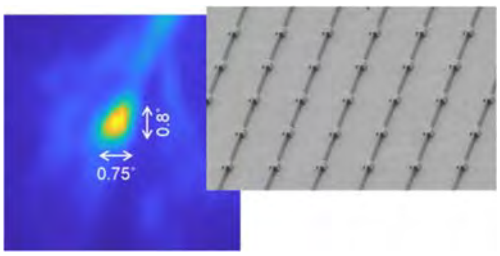

Figure 1 Far-field profile of a patch-antenna quantum cascade emitter (SEM image in the inset).

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All-optical photonic reservoir computing: harnessing complexity in nonlinear photonics

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Abstract

Combining a large number of elements may result in a complex system which is not trivial to handle, even if the response of each of its parts is perfectly well understood. Paradigms such as metamaterials or topological photonics provide considerable insight for harnessing complexity in order to create useful functions.
Another paradigm for creating complex but functional systems is reservoir computing (RC) [1]. The main idea is that interconnected nonlinear “nodes” (which can be almost anything) react to a time-dependent input with a rich dynamics. The system “learns” to produce the correct output by adjusting a linear combination of the values of these nodes; which is much less computational intensive than current methods in AI. RC is intrinsically resilient against fabrication tolerances, as its internal wiring may even be random and it has been implemented in many physical systems. RC have been demonstrated using telecom components in an optical or electro-optical feedback loop, frequency multiplexing, spatial multiplexing in free-space optics and photonic integrated circuits [2]. All-optical RC has already been proposed, yet the experimental demonstration have mostly relied on the detection playing the crucial role the nonlinear transfer function; thus, while propagating through the reservoir, the signal crosses from the optical to the electrical domain and vice-versa.

Here we present and discuss an entirely photonic RC, where nodes are nonlinear optical resonators coupled evanescently. Driven with large enough power the system develops a fairly complex dynamics and may even be chaotic. Yet, we show that the system can be controlled in order to provide useful response [3]. As an example, we show in simulations that the system is capable of undoing nonlinear distortion in coherent optical communications all-optically [4]. Implications are relevant, when considering the energy budget for the conventional digital implementation of this task. On the other hand, our results provide guidelines for the generation of nonlinear resonators optimized for photonic computing [5].

The all-photonic RC paradigm is general enough to benefit from a variety of photonic technologies providing enough complexity.

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Recent advances in topology optimization for meta-optics inverse design

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Abstract

Inverse design methodologies have revolutionized the way novel nanophotonic devices are conceived and engineered. Traditional design approaches often involve trial and error, limiting the exploration of complex parameter spaces and hindering the discovery of optimal device configurations. Adjoint-based topology optimization offers a systematic framework to address this challenge by leveraging the principles of gradient-based optimization. By efficiently computing the gradients of objective functions with respect to design parameters, adjoint methods enable the rapid exploration of vast design spaces, leading to the discovery of unconventional and highly efficient nanophotonic devices. In this talk, I will focus on recent research carried out in my group on advanced methodologies for inverse design, including for the design of photonic components such as waveguides, resonators, and metasurfaces. I will present inverse design techniques for the broadband topology optimization of metallic and dielectric nanostructures with arbitrary optical dispersion [1], and also discuss the optimization of the scattered field by a nanostructure based on objectives specified in terms of multipoles [2]. I will discuss novel devices conceived via inverse design, such as an integrated beam splitter with arbitrary phase at the output ports [3], and plasmonic nanostructures supporting anapole states for metamaterials transparency [4].

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Material platforms for biophotonic applications of holographic metasurfaces

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Abstract

Holographic Metasurfaces (HMSs) are ideally suited for tailored light-matter interactions at the micro and nano scales, typical of biophotonic applications. HMSs can be used to control the optical landscape in the proximity of biological specimens, surpassing the constraints of traditional microscopy approaches. Different materials and meta-atoms configurations present opportunities and challenges that determine their suitability and success for biophotonic experiments.

Here, we will present and discuss critically several platforms that we developed in the context of sensing, imaging, and optical manipulation.

The first platform is based on reflective-type meta-atoms based on a popular metal-insulator-metal approach based on Panchratnam-Berry phase elements [1]. At variance with standard solutions, our meta-atoms also host photonic resonances that depend on the refractive index of the surrounding medium. These HMSs have successfully been used for sensing [2] and trapping applications, in the near infrared. Importantly, we demonstrated that these HMSs offer the same trapping stiffness produced by expensive and bulky high NA microscope objectives [3].

A second platform is based on ceramic metasurfaces, used in transmission. We recently demonstrated that ZrO_2-based meta-atoms permit the shift of the operation wavelength to the blue region, which is of pivotal importance in biophotonic experiments. Using this approach, we demonstrated the first integrated trapping experiment below the wavelength of 500nm [4]. Additionally, the platform offers other unique advantages that make it ideal for use in extreme environments.

Lastly, we will show that simple polymeric metasurfaces can create high-quality holograms [5]. Photonic metasurfaces with sides of a few tens of micrometers can be manipulated as a precise tool inside microfluidic chambers, to pump whispering gallery modes lasers [6]. These metasurfaces also offer exceptional mechanical stability, which makes them ideally suited to study the optomechanical behavior of single molecules and living cells.

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Metasurfaces for enhanced Raman scattering and photocatalysis

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Abstract

Dielectrics are a new frontier for Surface Enhanced Raman Scattering. They can serve either as a complement or an alternative to conventional, metal-based SERS, offering key advantages in terms of low invasiveness, reproducibility, versatility and recyclability. In comparison to metals, dielectric systems are characterized by a much greater variety of parameters and properties that can be tailored to achieve enhanced Raman scattering or related effects. Light trapping and sub-wavelength focusing capabilities, morphology and size-dependent resonances, control of band gap and stoichiometry, charge transfer between substrate and molecules and vice-versa are a few examples of the manifold opportunities associated to use of dielectrics as SERS-active materials [1,2]. In this context, dielectric metasurfaces, which can be designed to manipulate light with unprecedent control, represent an exciting, yet still quite unexplored field for Raman spectroscopy and photocatalysis.

Here we will show how metasurfaces based on TiO_2 optical antennas can be exploited to enhance Raman scattering, providing a level of reproducibility and reliability that overcomes conventional plasmonic SERS [3]. This approach can be extended to the study of light-driven surface processes [4], allowing to finely control selectivity and efficiency of photocatalytic reactions.

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Energy and frequency manipulation with temporal interfaces

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Abstract

Recent progress in the study of highly nonlinear natural and artificial materials has sparked renewed interest in the extension of metamaterial concepts to the temporal domain. Until very recently, however, the temporal duals of basic scattering phenomena, such as reflection and diffraction, were never demonstrated for electromagnetic waves. Recently, following theoretical advances in this area [1], a temporal metamaterial was implemented using a structure capable of abruptly changing its electromagnetic properties within a time interval shorter than a single temporal oscillation cycle of the waves propagating in it. Such metamaterial can realize temporal interfaces dual to spatial ones. Temporal reflection of broadband pulses and the temporal analogue of an antireflection coating were observed in this platform [2]. Thanks to the insights obtained in the experiment, we recently uncovered a need for generalized boundary conditions, which go beyond those so far assumed in the literature on time-varying media.

Moreover, by exploiting the temporal interference between multiple waves, counter-propagating through such a time-metamaterial, we were also able to engineer synthetic collisions between microwave pulses, whose nature can be tuned from inelastic to super-elastic by varying the relative phase between them, realizing a broadband, phase-tunable temporal analogue of coherent control phenomena, such as coherent perfect absorption and lasing, and enabling a new form of pulse shaping based on the mutual sculpting of electromagnetic waves [3]. During the talk, we will present preliminary experimental results for photonic collisions at optical frequencies, and discuss implications of this concept for quantum light, highlighting the interesting opportunities arising in the quantum limit for advanced frequency manipulation and quantum state engineering.

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Temporal diffraction and synthetic motion from time-varying metamaterials

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Abstract

Metamaterials have revolutionised the way we control light transport and generation. Yet, to date, they rely on static and passive architectures, only redistributing incident wave energy - for example in a metalens, or a cloak - with no power to locally absorb or produce it to enhance responses. Instead, upon time-modulation, energy can be exchanged between the wave and medium, the wave frequency changes, and the propagation is no longer symmetric under an inversion of time [1]. Here I will discuss our first steps towards ultrafast driven photonic systems, able to convert energy to function and perform actions. I will report on experimental double-slit time diffraction at optical frequencies in time-varying metamaterials [2,3] where the interference appears as a frequency broadening with a sinusoidal modulation of the light spectrum. I will introduce synthetic motion, and show how we can experimentally realise superluminal motion of a scatterer and observe its spatio-temporal diffraction [4]. Time-varying metamaterials are opening an exciting path towards the spectral synthesis of waves and applications such as signal processing and neuromorphic computation.

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Extreme Space-Time Optics & Quantum Meta-Photonics

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Abstract

We first discuss all-optical modulation with single photons using electron avalanche, resulting in record-high nonlinearities. Then we show that transparent conducting oxides (TCOs) operating in the near-zero index (NZI) regime can provide strong single-cycle modulation, thus enabling novel photonic time crystals. Finally, we discuss scalable quantum photonics with single-photon emitters in silicon nitride that we recently discovered as well as the intriguing possibility to generate indistinguishable single photons by using plasmonic speedup that could enable important quantum photonics applications, including quantum communication and quantum computing.