Epsilon-near-zero technologies as an optical interface to harsh-environment silicon carbide sensors (ENZSICSENS)

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ABSTRACT Epsilon-near-zero (ENZ) media, i.e., media with a near-zero permittivity, offer a unique regime for light-matter interactions, where even the geometry of the device plays a qualitatively different role. Silicon carbide (SiC) is a polar dielectric exhibiting a high-quality ENZ response at thermal infrared frequencies. In ENZSICSENS, we combine ENZ media and SiC to enable a novel technology of thermal emitters, uniquely characterized by their geometrical flexibility. Leveraging our expertise in nanofabrication and FTIR spectroscopy, we have demonstrated proof-of-concept prototypes of SiC-ENZ thermal emitters. Our devices find applications as an optical interface with SiC-MEMS sensors, energy management, thermal camouflage and optoelectronics.

Keywords: Nanophotonics, thermal emitters, microelectromechanical systems, metamaterials, epsilon-near-zero media

1. INTRODUCTION

As the permittivity of a medium approaches zero, $\varepsilon \to 0$, the wavelength of light in such a medium effectively stretches, and the spatial and temporal variations of the electromagnetic field decouple. For this reason, epsilon-near-zero (ENZ) media represent a unique regime for light-matter interactions, characterized by qualitatively different wave phenomena. Beyond being a thrilling theoretical concept, there are multiple physical realizations of ENZ media, based either in continuous media (i.e., conventional materials) or metamaterials. For example, silicon carbide (SiC) is a semiconductor with excellent electrical, mechanical, thermal and chemical properties, being a material of choice for harsh-environment sensors, microelectromechanical systems (MEMS) and power electronics. SiC also exhibits a high-quality optical ENZ response in the thermal infrared, within the atmospheric window.

Project ENZSICSENS aims to technologically exploit the unusual wave phenomena in ENZ media using SiC as a material platform. It seeks to take advantage of the unique properties of ENZ media, while simultaneously searching for synergies with conventional technological applications of SiC. In ATTRACT Phase 1, we have proposed and experimentally demonstrated a new class of thermal emitters, where the ENZ response provides an unprecedented degree of geometrical flexibility and important technological advantages with respect to thermal emitters based on conventional photonic nanostructures.

2. STATE OF THE ART

Thermal emitters **-** Thermal emission and/or the absorption of infrared radiation by photonic nanostructures is a critical operational part of multiple technologies including heat-management, light sources, thermal camouflage, smart clothing, bioengineering, sensors and optoelectronic devices [1]. However, following black-body radiation, thermal fields are broadband and stochastic, hindering their manipulation with conventional optical techniques. Typically, engineering thermal fields involves improving their poor spatial coherence by locking them to well-defined optical modes induced by suitably designed nanostructures [2]. Examples of these nanostructures include interfaces supporting surface plasmons, optical resonators, photonic crystals, metamaterials, directional filters, etc [3]. All these approaches share the limitation that precise nanofabrication is required to shape nanostructures supporting the optical modes that induce the desired shape into the thermal fields. This fabrication complexity ultimately limits their large-scale applicability.

Epsilon-near-zero (ENZ) media, i.e., media with a near-zero permittivity, offers a qualitatively different regime for light matter interactions [4-5]. In essence, when the permittivity of a material approaches zero, $\varepsilon \to 0$, the wavelength is effectively enlarged, $\lambda \to \infty$, leading to anomalous field distributions characterized by a spatially static character, while harmonically oscillating in time. In turn, these field solutions lead to a plethora of exotic wave phenomena, including perfect transmission

through deformed waveguides, geometry-invariant resonant cavities, non-radiating modes, and violation of effective medium theories. Similarly, we demonstrated that the enlargement of the wavelength results in an *intrinsically (material-based) enhanced spatial coherence*, allowing for the directional manipulation of thermal fields, quite independently of the geometry of the system [6]. ENZ media is also characterized by a diverging medium impedance, $Z = Z_0/\sqrt{\varepsilon} \rightarrow \infty$. Importantly, high-impedance boundaries are one of the most successful approaches for the design of low-profile electromagnetic absorbers concentrating the dissipation in a thin resistive film [7]. Therefore, ENZ media provides a *material-based approach* to some of the most desirable characteristics for the design of thermal emitters.

Silicon carbide (SiC) is a polar dielectric exhibiting a highly reflective band at MIR frequencies, the Reststrahlen band, delimited by the transverse (TO) and longitudinal optic (LO) phonon frequencies [8]. Within this band, SiC supports surface phonon polaritons (SPhPs) with lifetimes 3 orders of magnitude longer than those of plasmons in noble metals. With these exceptional optical properties, SiC has enabled the observation of extraordinary tranmission, superlensing, deeply subwavelength resonators, coherent thermal sources, sensing of sub-nanometric thin-films and strong coupling with vibrational modes. In addition, SiC exhibits a near-zero permittivity $\varepsilon(\lambda_p) \sim 0$ around its plasma frequency $\lambda_p = 10.3\,\mu m$, being one of the highest-quality epsilon-near-zero (ENZ) materials known to date.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

In ENZSICSENS, we have harnessed the unique optical properties of SiC at MIR frequencies, including its high-quality ENZ response, to demonstrate a *novel class of thermal emitters with an unprecedented degree of geometrical flexibility*. In our devices, two key optical properties involved in the design of a thermal emitter, spatial coherence and a high-impedance boundary, are directly obtained from the material response of SiC. In this manner, efficient thermal emitters can be developed without the need of complex nanofabrication processes. First, exploiting an intrinsically enhanced spatial coherence makes it possible to obtain highly-directive thermal emitters, where the energy is routed into the directions of interest. Second, high-impedance boundaries maximize the electric field on the surface of the substrate (by contrast with conventional mirrors), strengthening the absorption within and emission from ultra-thin metallic layers with thicknesses in the nanometric or even atomically-thin scales.

We note that near-unity efficiency emitters can be designed in a number of ways by increasing the complexity of the geometry of the device, at the cost of increasingly demanding nanofabrication processes. Therefore, the breakthrough character of the project is not based on beating the performance of previous technologies of thermal emitters. On the contrary, it offers a disruptive technology with qualitatively different properties. Specifically, our emitters exploit the fact that the optical properties enabling thermal emission are intrinsic to the material in order to obtain a superior geometrical flexibility.

Our new design philosophy offers the following important technological advantages: (i) Our devices do not require from the precise fabrication of photonic nanostructures. Thus, they directly appeal to large-scale production, large-area and conformal applications. (ii) The high degree of geometrical flexibility simplifies the integration of the devices into more complex systems. (iii) In fact, our current material platform is transparent at optical frequencies, opening up their integration within architectures for transparent electronics and smart windows. (iv) SiC a semiconductor with excellent electrical, mechanical, thermal and chemical properties, being in many cases the material of choice for harsh-environment sensors and power electronics. The integration of thermal emitters present clear synergies with these technologies, acting as an optical interface that either enables readout operations and/or helps in the energy management. (v) An intrinsic high-impedance boundary makes it possible to concentrate the absorption within ultra-thin metallic films. Reducing the amount of material where the absorption takes place can both extend and speed up the reconfigurability of dynamical thermal emitters, as well as to improve photothermal modulation. (vi) Concentrating the absorption in extremely thin metallic layers enables the enhancement of light-matter interactions in sub-nanometre and atomically-thin materials, and it might become a powerful tool for basic research on those extreme structures.

With these unique technological advantages, our devices can be considered a novel class of thermal emitters, with the potential for a widespread impact in multiple technologies.

4. PROJECT RESULTS

In ENZSICSENS, we have demonstrated several thermal emitters based on the unique optical properties of ENZ media and their implementation based on SiC. Figures 1-2 reports one of our devices, which serves to illustrate some of the main technological advantages of this technology. It consists of a very thin titanium (Ti) metal layer (2nm) deposited on top of a SiC substrate acting as

an intrinsic high-impedance boundary at its ENZ wavelength around $\lambda \sim 10.3\,\mu m$. As shown in the photograph reported in Fig. 1(a), the entire system remains transparent at optical frequencies, so that the device is compatible with transparent electronics and smart window applications. The SEM image of the system, reported in Fig. 1(b), provides a clearer view of the metal film on top of the SiC substrate.

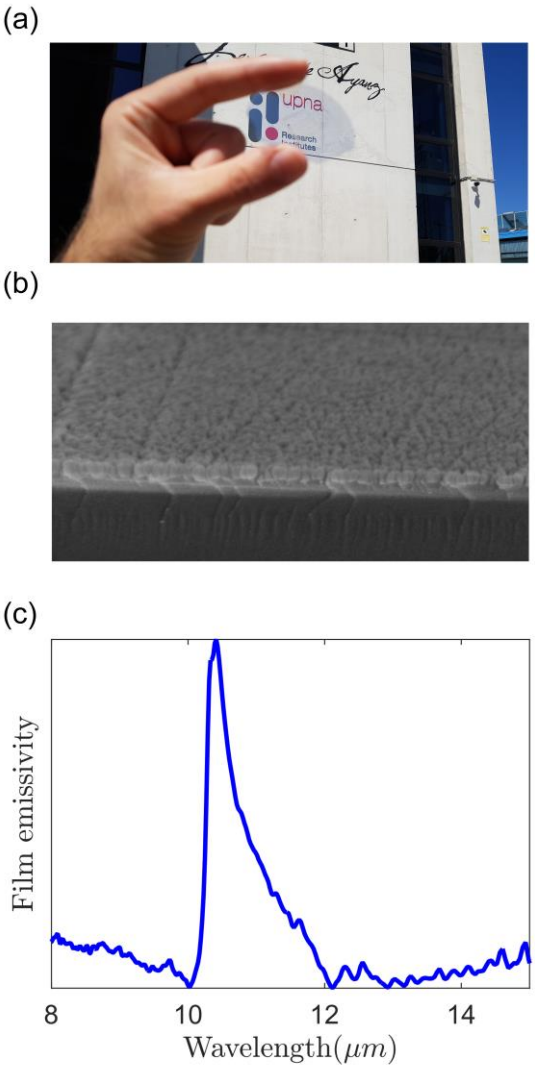

Fig. 1. (a) Photograph of the device under sunlight outside our lab. **(b)** SEM image of the device revealing the metal film deposited on top of the silicon carbide (SiC) substrate. **(c)** Film emissivity spectra within the thermal atmospheric window (8 – 14 μm), showing that thermal emission is dominated by a resonant spectral feature around the epsilon-near-zero (ENZ) wavelength λ = 10.3 μm.

Fig 1(c) depicts the film emissivity in the atmospheric window (8 μm – 14 μm) measured via FTIR spectroscopy. The measurement shows that the film emissivity is characterized by a resonant peak around the ENZ wavelength of SiC ($\lambda \sim 10.3$ μm). In fact, the emission in the entire atmospheric window is dominated by this singular spectral feature. In addition, we note that the absorption is concentrated within the nanometer-thin metal film. The fact that all the emission in the atmospheric window can be concentrated into a single spectral feature originated from a highly confined spatial suggests that this is an ideal structure for a dynamic control of thermal emission. Therefore, our technology appeals for dynamical emitters for communication, thermal camouflage, radiative cooling and energy management applications.

As anticipated, one of the unique characteristics of our technology of thermal emitters is that it provides an unprecedented degree of geometrical flexibility. Typically, the design of high-impedance boundaries involves metamaterial structures consisting of carefully designed resonators and spacers. By contrast, a material based (intrinsic) high-impedance boundary exhibits this property independently of the geometry of the boundary. In other words, it does not suffer from spatial dispersion typical of metamaterial structures, and its geometry (e.g., the curvature radius) is not limited by the size of the unit cell. Fig. 2 gathers a set of full-wave numerical simulations that illustrate this point. Specifically, the geometry of the system has been selected to emulate an arbitrarily-shaped irregular profile. In addition, the size of the system has been parametrized with a length scale parameter, L, in order to consider irregular profiles with subwavelength ($L \sim 500\,nm$), comparable to the wavelength ($L \sim 5\,\mu m$), and larger than the wavelength ($L \sim 50\,\mu m$) length scales. The film absorptivity for these different length scales is reported in Fig. 2(b). It can be concluded from the figure that the spectral features are independent of the use of a substrate with an irregular profile, as well as the length scale of its geometrical features. The operating principle behind this effect can be more clearly appreciated in the electric field distribution reported in Fig. 2(c).

These results demonstrate that our thermal emitters can operate even in substrates with arbitrarily-shaped irregular profiles, and even in subwavelength, comparable to the wavelength and larger than the wavelength scales. We are currently working in experimentally demonstrating this concept, and several prototypes of substrates with an irregular profile have already been fabricated. This is a unique feature or our devices stemming from the fact that we use material-based high-impedance boundary, instead of using a photonic nanostructures to artificially create one. As a result, our devices exhibit an unprecedented degree of geometrical flexibility posing technological advances in terms of the integrability of the system and operation in harsh-environments.

Additional experimental results can be found in our scientific manuscript [10]. Information about the methods employed as well as practical considerations such as the role of roughness is also available. As reported in the manuscript, we have also developed a theoretical framework that provides a theoretical upped bound on the performance of our system as a function of the materials available.

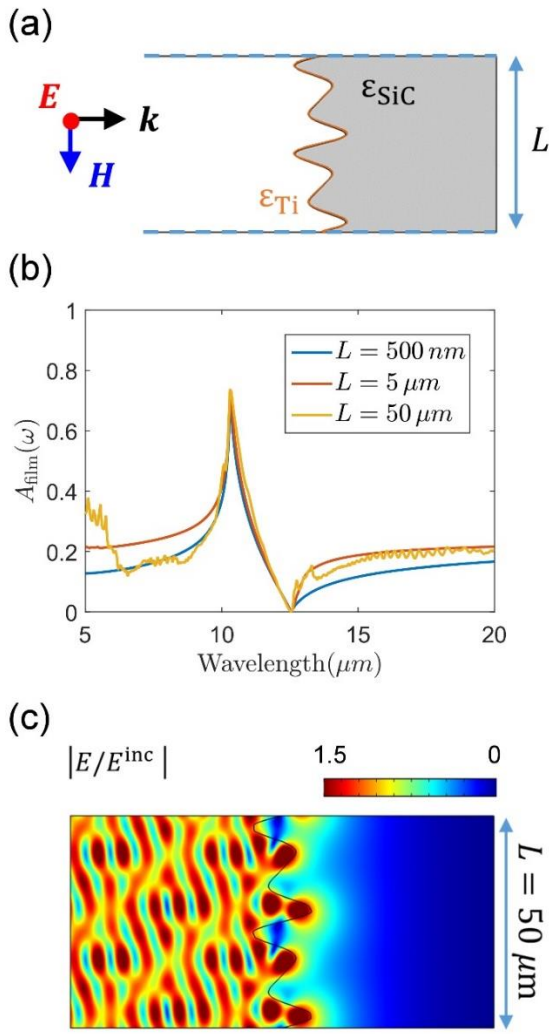

Fig. 2. (a) Sketch of the simulation setup. **(b)** Numerical prediction of the film absorptivity within the atmospheric window for titanium films on top of a SiC substrate. **(c)** Electric field magnitude distribution showing an enhanced concentration at the surface of the substrate.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

Project ENZSICSENS has allowed us to push forward our theoretical results to the point of proof-of-concept experimental demonstration. Therefore, our technology is currently at TRL 3-4. Moving forward with the technology scaling towards TRL 5-7 will require to demonstrate the technology into an industrially relevant environment. In our case, this implies incorporating our optical interface into a larger scale system such as harsh-environment SiC sensors or a smart window. To this end, we need the cooperation of strategic partners described in Section 5.2.

5.2. Project Synergies and Outreach

Scaling up our technology for achieving TRL 5-7 will require from adding strategic partners to the consortium. At the research level, our team would greatly benefit from cooperation with research groups on material science. While our technology is currently based on SiC, there are multiple realizations of ENZ media, such as doped-semiconductors (aluminium -zinc-oxide (AZO), cadmium oxide (CdO), etc…). These materials would enable the operation in other frequency regimes, of particular interest being the near-infrared including telecommunication wavelengths. This would open the possibility to explore additional applications for our technology, particularly for optoelectronic devices. In addition, our expertise is centred on the theoretical modelling and design of nanophotonic systems, nanofabrication and FTIR spectroscopy. The technology scaling of our project will require from the cooperation with systems engineers, having the ability of incorporate our optical interface into their system, while taking full advantage of the unique geometrical flexibility offered by our technology. We are currently targeting harsh-environment SiC-MEMS sensors and smart windows.

In ENZSICSENS we have been compromised to the public dissemination and outreach activities based on our results. We have written a manuscript with the results of the project [10], and we are preparing a second one. We have organized a convened session at “The 14th International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials’2020)”, entitled “Epsilon-near-zero media: theory and applications”, where we will publicize the results of the project among other experts in the field.

5.3. Technology application and demonstration cases

For the ATTRACT Phase 2 we are currently targeting two different technology demonstration cases:

(i) Demonstration of ENZ thermal emitters directly integrated on SiC-MEMS for industrial harsh-environment sensing applications.

(ii) Demonstration of a large-area, optically transparent, dynamical ENZ thermal emitters, with exhibiting thermal homoeostasis and/or communication capabilities for smart window applications.

The sensor developed in (i) have direct applications in energy, aerospace, automotive, and communication market sectors. Beyond purely industrial applications, harsh environment sensors are also required for the exploration of the bottom of the ocean, space and the human body. The smart thermal materials developed in (ii) has direct application as smart windows, energy management and thermal camouflage.

The technologies associated with the proposed demonstration cases perfectly align with the strategy of the European Commission for addressing societal challenges. In particular, both the "Secure, Clean and Efficient Energy" and "Smart, Green and Integrated Transport". Harsh-environment sensors and smart windows are likely to play a significant role in addressing these challenges.

5.4. Technology commercialization

At this point we have not initiated concrete steps toward the commercialization of our technology. For the elaboration of a technology commercialization plan, we are currently seeking advice from our host institution, the Institute of Smart Cities (ISC) at the Public University of Navarre (UPNA), which has a successful track record in the creation of spin-offs and collaboration with companies for the commercialization of the technology developed at ISC-UPNA.

5.5. Envisioned risks

The main challenge of ATTRACT Phase 2 will be the technology scaling of a new class of thermal emitters from TRL 3-4 to TRL 5-7. Being a technology with a qualitatively different response, the core risk is that it is very challenging to predict what will be the performance of our devices in an industrially relevant environment. The importance of the risk is mitigated by the fact that our thermal emitters indeed feature unique properties, such as geometrical flexibility, which would make them competitive even if they are slightly less competitive in traditional performance parameters. An additional challenge and core risk is the need to expand our team to a bigger consortium. However, this risk is mitigated by the previous experience of our team in coordinating collaborative actions.

5.6. Liaison with Student Teams and Socio-Economic Study

The members of the consortium have ample experience in coordinating research and education activities. In fact, collaboration between students and research groups is actively promoted by the institutions composing the consortium. Specifically, we have planned the following actions:

(i) We will offer multiple MSc. final projects, allowing for MsC to actively participate in the project while acquiring their first experience as researchers. (ii) The host institutions of the consortium offer "collaboration scholarships" sponsoring students to collaborate with research groups. We have already benefited from these scholarships and we plan to continue with this activity within the framework of ATTRACT Phase 2. (iii) We will organize a short course for MsC. students on the topic of the project, which will be publicize at a European level.

All members of the consortium will be available to contribute to the expert-driven socio-economic study of the ATTRACT initiative, participating in interviews, providing technology impact references and/or any information required.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] Boriskina, Svetlana V., et al., 2017. Heat is the new light, Optics and Photonics News 28(11): pp. 26-33.
[2] Greffet, Jean-Jacques, et al., 2002. Coherent emission of light by thermal sources, Nature 416(6876): pp. 61-64.
[3] Baranov, D. G. et al., 2019. Nanophotonic engineering of far-field thermal emitters, Nature Materials 19: pp. 920–930.
[4] Liberal, I., & Engheta, N., 2017. Near-zero refractive index photonics, Nature Photonics 11(3): pp. 149-158.
[5] Reshef, O., De Leon, I., Alam, M. Z. & Boyd R. W., 2019. Nonlinear optical effects in epsilon-near-zero media, Nature Review Materials 4: pp. 535–551.
[6] Liberal I. & Engheta N. Manipulating thermal emission with spatially static fluctuating fields in arbitrarily shaped epsilon-near-zero bodies, Proceedings of the National Academy of Sciences 115: pp. 2878–2883.
[7] Tretyakov, S.A. & Maslovski, S. I., 2003. Thin absorbing structure for all incidence angles based on the use of a high-impedance surface, Microwave Optical and Technology Letters 38: pp. 175–178.
[8] Caldwell, J. D., et al., 2015. Low-loss, infrared and terahertz nanophotonics using surface phonon polaritons, Nanophotonics 4: pp. 44–68.
[9] Kim, J. et al., 2016. Role of epsilon-near-zero substrates in the optical response of plasmonic antennas, Optica 3: pp. 339–346 (2016).
[10] Pérez-Escudero, J.M., Buldain, I., Beruete, M., Goicoechea, J. & Liberal I., 2020. Silicon carbide as a material-based high-impedance surface for enhanced absorption within ultra-thin metallic films. *Under review.*