Can we Bring EM Enhancement to the Multi-wavelength Scale?

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Abstract

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Can we Bring EM Enhancement to the Multi-wavelength Scale?*

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Abstract – EM enhancement is typically a lensing-type of effect by which a wide input beam couples to spatially localized resonant modes as for example Mie plasmons, void plasmons or Mie modes at high refractive index particles. Accordingly, EM enhancement is inherently a sub-wavelength phenomenon. Here, we explore a different paradigm for EM enhancement that is based on EM energy being collected over large time intervals by means of an ultra-slow-light waveguide. With ab-initio simulations, we study the dynamic evolution of such EM enhancement. After more than 7000 wave periods we observe that an intensity enhancement of more than 50 can cover an area of more than 15 λfree2 with λfree being the free-space wavelength.

I. INTRODUCTION

Electromagnetic (EM) enhancement has been intensively investigated with various structures due to its relevance to a multitude of current photonic applications of high interest, from photovoltaics [1] and sensors [2]-[3] to color filters for information encoding [4] and enhanced thermal emission [5]-[6]. Typically, EM enhancement is achieved by coupling of an impinging beam to localized resonances such as Mie plasmons of individual plasmonic nanoparticles, shells or dimers [7]-[10], void plasmons [11]-[12] Mie phonon-polaritons [5]-[6], [13]-[15], or Mie modes at high refractive index dielectrics [16]. The enhancement of the electric field occurs without any violation of energy conservation, because a beam with a wider beam-waist compresses spatially around the aforementioned nano-/micro-structures. Because of this strong spatial compression effect the EM enhancement is strong in the close vicinity of the structured resonator element but decays very fast away from it. Many applications, such as SERS [2] rely precisely on this effect. However, there are applications that could benefit from perhaps more moderate values of EM enhancement, that however extends over larger, multi-wavelength-scale areas. This is true when it is important to harness a strong interaction between the EM-enhancing structure and non-linear or gain material.

II. SYSTEM UNDER STUDY

Here, we consider an alternative paradigm to investigate how far we would be able to push the spatial extent of EM enhancement beyond the sub-wavelength scale. We consider a previously studied ultra-slow waveguide [17]-[19]. The waveguide system comprises a negative-index-medium (NIM) slab waveguide [20] supporting backward-wave modes [21] in contact with a conventional positive-index medium (PIM) slab waveguide that supports forward-wave modes. The waveguide modes in the two waveguides strongly couple into a new mode entity with an entirely different dispersion relation, ω(kz), where ω represents the frequency of the mode and kz the wave vector along the guiding direction. The dispersion relation of the new composite mode, can be tailored to exhibit a near-zero group velocity, do/dkz with proper choice of the geometric parameters of the NIM and PIM slabs. There are certain advantages of this particular waveguide system: (i) PIM-NIM heterostructures can be easily designed to be mono-modal within a certain operational bandwidth [22] thereby addressing cross-modal talk losses. Cross-modal losses may have been a contributing issue to the overall losses problem in

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photonic-crystal-based slow-light waveguides [23], which exhibit only a low transmission within the slow-light window [24] (ii) The system can be designed to possess simultaneously a near-zero group velocity with a low group-velocity dispersion. This is a very important attribute. We showed in Ref. [18] that in order to practically achieve slow-light propagation having a near-zero group velocity is not a sufficient condition. The near-zero group velocity should be accompanied by also a low group-velocity dispersion.

We had shown previously that in the NIM-PIM bi-waveguide paradigm light may accumulates in the region where EM energy is fed into the waveguide via a side-coupling configuration similar to the Otto configuration [17]. We stress, this is true for a mode with a time-domain verified slow-light behavior; not all modes with near-zero group velocity, as predicted from frequency-domain calculations, satisfy this requirement. As we discussed above, the advantageous modes are the ones with a low value for the group velocity times group velocity dispersion product (see Ref. [18]). Here, in this work, we focus on investigating how to control the spatial extent of the EM enhancement within the waveguide by utilizing such type of suitable slow-light mode. We will also aim to understand the limits and dynamic evolution of such EM enhancement.

III. DISCUSSION

To study the dynamic evolution of the spatial extent of the electric-field enhancement we utilize the Finite Difference Time Domain method (FDTD) [25]. We look at the time-averaged electric-field intensity, averaged over a full wave cycle, \( T \), at different time instances. We observe as time progresses that the electric-field intensity enhancement with respect to the free-space electric field intensity, \( I_{\text{eha}} \), increases while at the same time the spatial extent of \( I_{\text{eha}} \) increases as well. This is true for the region within the NIM part of the bi-waveguide as \( I_{\text{eha}} \) in the PIM-part of the waveguide is not significant. In Fig. 1 we depict \( I_{\text{eha}} \) after the field has evolved for about 7000 wave periods, \( T \). Only part of the bi-waveguide is shown in Fig. 1 to focus on the region with significant \( I_{\text{eha}} \). From the field profile we determine that the area coverage corresponding to \( I_{\text{eha}} \) values more than 50 exceeds 15 \( \lambda_{\text{free}}^2 \), with \( \lambda_{\text{free}} \) being the free-space wavelength corresponding to the slow-light mode.

![Fig. 1. Time-averaged electric-field intensity, averaged over a full-wave cycle, \( T \), and normalized with the free-space time-averaged electric-field intensity, thus representing electric-field intensity enhancement, \( I_{\text{eha}} \). The depiction corresponds to fields that have evolved for about 7000 wave periods. We can clearly observe the spatial extent of quite large electric-field enhancement over several free space wavelengths, \( \lambda_{\text{free}} \).](image)

IV. CONCLUSION

We explored electric-field intensity enhancement covering multiple-wavelengths-scale areas. We achieved this by accumulating EM energy over time in a specially designed slow-light waveguide. This new paradigm can inspire systems that go beyond the typical sub-wavelength EM-enhancement schemes and can be important for active and non-linear photonic devices.
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REFERENCES

[22] A. Alu and N. Engheta, “Guided modes in a waveguide filled with a pair of single-negative (SNG), double-negative (DNG), and/or double-positive (DPS) layers,” IEEE Trans. Microwave Theory Tech., vol. 52, pp. 1999, 2004.