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Photonic crystal enabled THz sources, and one-way waveguides

Z. Wang\textsuperscript{(1)}, Y. Chong\textsuperscript{(1)}, A. Rodriguez\textsuperscript{(1)}, J. B. Abad\textsuperscript{(1)}, S. G. Johnson\textsuperscript{(2)}, J. D. Joannopoulos\textsuperscript{(1)}, M. Soljačić\textsuperscript{(1)}

\textsuperscript{(1)} Department of Physics, MIT, USA
\textsuperscript{(2)} Department of Mathematics, MIT, USA

We present two photonic crystal enabled platforms, exhibiting novel active optical phenomena. First, using a detailed theoretical and numerical analysis, we show how a Purcell-effect inspired nonlinear nanophotonic scheme could enable optimal and compact THz sources via optical difference frequency generation. Second, we show how electromagnetic one-way edge modes analogous to quantum Hall edge states, originally predicted by Raghu and Haldane in gyroelectric photonic crystals, can appear in more general settings. In gyromagnetic YIG photonic crystals operating at microwave frequencies, time-reversal breaking is strong enough that the effect is readily observable. We present our experimental results on this novel phenomenon.
Efficient low-power terahertz generation via Purcell-enhanced nonlinear frequency mixing

The discovery of Purcell effect more than sixty years ago [1], opened up the fascinating possibility of manipulating almost at will the rate of spontaneous emission (SE) of a quantum light emitter by modifying the electromagnetic density of states of the environment in which the emitter is embedded. With advent of concepts such as photonic crystals (PhCs), and thanks to the rapid development of improved nanofabrication techniques, the ability to control the SE of atoms, molecules, or quantum dots, has become of great importance as the basis for a broad spectrum of important applications in fields so diverse as illumination, biological and chemical sensing, harvesting of solar energy, or communications [2]. One of the most remarkable illustrations of this concept resides in the enhancement of the conversion efficiency of those nonlinear frequency mixing processes whose conversion efficiency is intrinsically very low. Of special interest, due to its considerable importance for applications [3,4] is the case of efficient terahertz (THz) generation.

In what follows, we present results on a scheme [6,7] that enables enhancement of the THz power generated via second-order nonlinear frequency downconversion by up to three orders of magnitude compared to conventional approaches. Using a classical analog of quantum mechanical Purcell effect, along with a detailed numerical analysis, we have demonstrated how the unique properties of photonic microresonators to confine light in subwavelength volumes for many optical periods can be tailored to dramatically reduce the pump power at which the theoretical maximum of THz generation predicted by the Manley-Rowe quantum limit is reached. As an example, we demonstrate that the scheme proposed here enables implementation of highly-efficient compact THz sources operating at room temperature and pumped by sub-μJ energy pulses, thus opening the way towards practical realization of a number of important applications in a broad spectrum of fields, ranging from communications to biomedical imaging.

Figure 1a displays a schematic of the proposed system. The power carried by two NIR beams of wavelengths λ₁ and λ₂ (playing the role of idler and pump beams, respectively, their corresponding power being P₁in and P₂in) is coupled, by means of an index-guided waveguide, to two high-order whispering gallery modes (WGM) supported by a dielectric ring resonator. These WGM at λ₁ and λ₂ are characterized by angular momenta m₁ and m₂, respectively. The ring resonator is in turn embedded as a dipole-like defect for λₖ, in an otherwise perfectly periodic THz-wavelength scale photonic crystal (PhC) formed by a square lattice of dielectric rods (see the corresponding electric field profile in Fig. 1b). Thus, in this case, the nonlinear frequency down-conversion interaction that takes places between the two NIR WGM’s circulating inside the ring resonator yields a current distribution that radiates inside the PhC cavity at the frequency difference ω₁-ω₂; the rate at which the radiation is emitted is strongly enhanced by the PhC
environment in which the ring resonator is embedded. In order to extract efficiently the THz output power \( P_T \) from the PhC cavity, we introduce into the system a photonic band-gap waveguide created by reducing the radius of a row of rods (see Figs. 1a and 1b). In addition, in order to break the degeneracy existing between the \( x \)-and \( y \)-oriented dipole defect modes, the radius of two of the nearest neighbors rods of the ring resonator is reduced with respect to the radius of other rods in the PhC. This configuration permits having a large value for the Purcell factor \( (Q_T/V_T) \), along with a high-Q resonant confinement also for the pump and idler frequencies. Figure 2b shows the structure that results from optimizing the geometrical parameters of the system for efficient generation at 1 THz, assuming a pump beam of wavelength \( \lambda_1=1550\text{nm} \), an idler beam with \( \lambda_2=1542\text{nm} \), and that the structure is implemented in GaAs (in which the relevant component of the nonlinear susceptibility tensor is \( d_{14}=274\text{pm/V} \)).

Figure 1c summarizes the results obtained in the continuous-wave (cw) regime. In these calculations we have assumed that \( P_{1\text{in}} = P_{2\text{in}} \) (the dependence of the results on the ratio \( P_{2\text{in}}/P_{1\text{in}} \) is shown in Fig. 1d) and a quality factor \( Q=5\times10^4 \) for the three frequencies involved in the frequency down-conversion process. This value for \( Q \) is compatible with both the absorption coefficient of GaAs at 1 THz (\( \alpha=0.5\text{cm}^{-1} \)) and with the experimental values for the quality factors obtained in similar configurations for the considered ring resonator and the photonic crystal cavity [2,5]. As shown in Fig. 1c, for values of \( P_{1\text{in}} > 0.01P_0 \) the conversion efficiency (defined here as ratio between the output power at THz and total input power at NIR frequencies) starts departing from the conversion efficiency predicted by the undepleted approximation, eventually reaching the maximum value predicted by the Manley-Rowe relation. As clearly shown, at the critical value of \( P_{1\text{in}} \) at which this maximum conversion efficiency is reached (in our case 0.19\( P_0 \), or equivalently 0.32W) the pump power that is coupled to the ring resonator is completely down-converted inside the system to power at THz and idler frequencies, giving rise to a sharp minimum in \( P_{1\text{tr}} \) and a maximum in \( P_{2\text{tr}} \).

To summarize, using a realistic classical analogy of the Purcell enhancement of the spontaneous emission rate of an atom inside a cavity, we predict that it is possible to dramatically enhance the conversion efficiency of a general difference-frequency downconversion process. By means of detailed numerical simulations, we have demonstrated that in the continuous-wave regime the pump powers required to reach quantum-limited conversion efficiency can be reduced to up three orders of magnitude with respect to the conventional approaches for THz generation employed up to date. In contrast to previous high-efficiency THz generation schemes, the concept introduced in our work opens, for the first time, the way to efficient THz generation from sources that are compact, turn-key, and low-cost, which we believe could enable a broader use of THz sources.
Figure 1. (a) Schematic of the triply-resonant nonlinear photonic structure analyzed in the text. $P_{1\text{in}}$ and $P_{2\text{in}}$ denote the input powers at the pump and idler frequencies, respectively; whereas $P_{1\text{tr}}$ and $P_{2\text{tr}}$ represent the corresponding transmitted powers through the structure. $P_{\text{THz}}$ stands for the THz output power. (b) Electric field profile (Ez) as obtained from FDTD calculations corresponding to the resonant mode appearing at 1THz in the structure shown in Fig. 1a. The value of the different geometrical parameters displayed in this figure are $a=102\mu m$, $d_1=40.8\mu m$, $d_2=5.3\mu m$, $d_3=4.0\mu m$, and $w=0.8\mu m$. Inset displays an enlarged view of the electric field profile (pointing along the z-direction) corresponding to a whispering gallery with $m=572$ circulating inside the dielectric ring shown in the main figure. The geometrical parameters defining the ring resonator are also shown in the inset, $R_{\text{ext}}$ and $R_{\text{int}}$ being 40.1$\mu m$ and 30.5$\mu m$, respectively. Yellow areas in both the main and inset figures represent GaAs regions, while white areas represent air. (c) Ratio between the total output power emitted by the system at 1 THz and the total input power at the NIR pump and idler frequencies. The results for the three frequencies involved in the considered nonlinear down-conversion process are displayed ($\omega_1, \omega_2, \omega_\text{f}$ correspond to the pump, idler, and final THz frequencies, respectively). (d) Solid line renders the dependence between $P_{2\text{in}}$ and $P_{1\text{in}}$ that yields the maximum THz conversion efficiency in the analyzed configuration. Blue line represents the case $P_{2\text{in}} = P_{1\text{in}}$. Yellow and blue areas represent the regions of mono-stability and multi-stability, respectively, in the space of parameters $\{P_{1\text{in}}, P_{2\text{in}}\}$. 
Uni-directional waveguides for light

Electromagnetic one-way edge modes analogous to quantum Hall edge states, originally predicted by Raghu and Haldane [8] in gyroelectric photonic crystals, can appear in more general settings. In gyromagnetic YIG photonic crystals operating at microwave frequencies, time-reversal breaking is strong enough that the effect is readily observable [9]. We show [10] for the first time an experimental one-way structure in which microwave light flows losslessly around obstacles or defects. This concept, when used in lightwave circuits, such as fiber-optic communication links, might one day reduce their internal connections to simple one-way conduits with much improved capacity and efficiency. The one-way waveguide, also known as chiral edge states (CESs), resides at the boundary of a topological photonic crystal, where photons travel in the same fashion as electrons in integer quantum Hall systems. Through the application of an external magnetic field, this specially designed waveguide induces unusual restrictions to the propagation of the light inside it, as illustrated in Fig. 2. In conventional optics, light reflections present a major roadblock to light-driven circuits reaching the same level of sophistication as widely used microelectronic circuits. A variety of practical applications, such as optical isolation and optical information storage could potentially benefit from the novel and unparalleled one-way photonic behavior observed.
Figure 2. (a) Schematic of the experimental setup used to measure the transport properties of the topological states. Numerical modeling reveals (b) the one-way propagation and (c) the complete suppression of scattering. (d) Network analysis at microwave frequencies confirms the strong suppression at mid-bandgap frequencies.
References