Terahertz Light Sources by Electronic-Oscillator-Driven Second Harmonic Generation in Extreme-Confinement Cavities

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Abstract: We propose a coherent THz source by efficient, cascaded second harmonic generation from electronic oscillators. We introduce hybrid dielectric cavity designs combining extreme field concentration in high-Q resonators with phonon-resonance-enhanced nonlinear materials.

The majority of sources of coherent optical radiation rely on laser oscillators driven by population inversion. Despite their technological importance in communications, medicine, industry, and other fields, it remains a challenge to produce high-power oscillators in the spectral range of 0.1-10 THz (the “terahertz gap”), a frequency band for applications ranging from spectroscopy to security and high-speed wireless communications [1]. Within the THz gap, sources based on electronic methods become inefficient above \( f_{\text{max}} \sim 100-300 \) GHz [2]. On the other hand, THz sources derived from population inversion nowadays have low efficiencies, require cryogenic cooling, or rely on expensive ultra-fast lasers [3]. Here, we propose a way to produce coherent radiation spanning the THz gap by efficient second-harmonic generation (SHG) in low-loss dielectric structures, starting from electronic oscillators (EOs) in the \( \sim 100 \) GHz range. To achieve this goal, we introduce hybrid THz-band dielectric cavity designs that combine (1) extreme field concentration in high-Q resonators with (2) nonlinear materials enhanced by phonon resonances.

As indicated in Fig. 1, we consider an electronic source at the low end of the THz gap that drives the first stage of second-harmonic generation (SHG) in a dielectric cavity. This cavity is made of a low-loss linear medium that creates a deep sub-wavelength region of high electric energy density inside a \( \chi^{(2)} \) nonlinear material. After the first conversion step, the output is directed to the next cavity. Figure 1(b) illustrates the SHG cascade process using

![Fig. 1. (a) Terahertz sources and proposed work. THz gap is shaded in red; available output power in 100 GHz - 10 THz range is limited. Our proposed device starts with an EO input at \( \sim 1 \) W, \( \sim 100 \) GHz (circled) to generate output power crossing the THz gap by cascaded frequency doubling. (b) Schematic of spectrum-spanning nonlinear frequency synthesis in PhC cavities. The fundamental mode at \( \omega_{a} \) is coupled to the second-harmonic mode at \( \omega_{b} = 2\omega_{a} \) in the first cavity with coupling rate \( g \). The output at \( \omega_{b} \) couples to the next cavity, cascading in a sequence of frequency doubling steps. After \( N \) steps the final output is at \( 2^{N} \omega_{a} \).](image-url)
a doubly-resonant photonic crystal (PhC) cavity. Pumping mode $a$ with a power $P_p$ generates a field in mode $b$ with efficiency $\eta_{\text{SHG}}$

$$\eta_{\text{SHG}} \equiv \frac{P_{\text{SHG}}}{P_p^2} = \left(\frac{64}{\hbar \omega_a^4}\right) \cdot g^2 Q_a^2 Q_b^2 \cdot \eta_c,$$

where $\eta_c$ is the input-output coupling efficiency, $Q_a$ and $Q_b$ are the quality factors of the fundamental (FD) and second-harmonic (SH) modes, respectively, and $g$ is the nonlinear coupling rate [4].

Dielectric cavities with high quality factors have been demonstrated that introduce tip structures resulting in extreme field enhancement at the tip [5–8]. We apply this field concentration principle to the THz regime to design hybrid-material PhC and ring cavities with large SHG conversion efficiency. Fig. 2(a) shows the FD (top) and SH mode (bottom) of our 1D PhC cavity design. The dielectric field concentration tips are introduced in the center hole. Fig. 2(b) shows a top view of our ring cavity (middle) and cross sectional profiles of the FD (left) and SH mode (right). We theoretically estimated the first- and second-order susceptibility of several promising materials in the terahertz region: GaAs, GaP, ZnTe, LiNbO$_3$, and LiTaO$_3$ (Fig. 2(c)). From calculations of non-depleted and absolute conversion efficiencies of our devices over a sequence of cascaded frequency doubling steps (Fig. 2(d)), we theoretically predict conversion efficiencies of $> 10^3$ $\%$/$\text{W}$ and the potential to bridge the THz gap with 1 W of input power. Our approach enables efficient, cascaded parametric frequency converters, representing a new generation of light sources extensible into the mid-IR spectrum and beyond.

Fig. 2. (a) Top-view of field profiles ($\log_{10}[|E/E_{\text{max}}|^2]$) of the PhC cavity modes at $\omega_a$ and $2\omega_a$ and close-ups of the nonlinear tips. (b) Side-view and close-ups of field profiles in the ring. Scale-bars: $\lambda_a/5$ ($\lambda_a/1000$ for close-ups). (c) Second-order susceptibility, $|\chi_j^{(2)}(\omega, \omega, 2\omega)|$ predicted from theoretical models (tensor components indicated in parentheses). Crosses: available experimental data [9]. Transverse optical phonons can be driven by EM waves, resulting in large linear susceptibilities. The nonlinear susceptibilities are higher on resonance because they are proportional to the linear susceptibilities at the frequency components of interest. (d) Maximum SHG efficiency for doubling frequencies, in $\%/$W. Solid and hollow markers represent the present design and near-future designs with improved $Q$, respectively.

References

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