Broadband Sum–Frequency Generation of Spectrally Incoherent Pulses

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High-energy nanosecond solid-state laser systems operating in the near infrared require frequency conversion to improve the efficiency of laser–matter interaction. This is generally done with a sequence of two nonlinear crystals, one for frequency doubling from 1ω (1053 nm) to 2ω (526.5 nm) and one for mixing of the resulting 2ω with the remaining 1ω to generate 3ω pulses (351 nm) (Ref. 1). The spectral acceptance of the tripling stage can be increased using two crystals or angular dispersion at 1ω (Refs. 2 and 3), but neither scheme allows for efficient operation beyond ~1 THz with incoherent nanosecond pulses. Simulations show that spectrally incoherent broadband pulses can mitigate the detrimental laser–plasma instabilities and on-target beam imprint, therefore increasing the coupling efficiency of energy into the target.[4]

A novel sum–frequency generation (SFG) scheme based on a noncollinear interaction between a 1ω broadband angularly dispersed pulse and a narrowband 2ω pulse allows for efficient frequency conversion into broadband 3ω pulses. Experimental results are in excellent agreement with simulations, demonstrating the generation of spectrally incoherent 3ω pulses with bandwidths larger than 10 THz in a relatively thick 1-cm KDP crystal. This scheme can be implemented with commercially available large-aperture diffraction gratings and nonlinear crystals to support a new generation of high-energy laser facilities delivering spectrally incoherent pulses.

The wave-vector mismatch for SFG of a broadband angularly dispersed pulse (frequency $\omega + \Omega$, angular dispersion D) with a narrowband pulse (frequency 2ω) in a noncollinear geometry [Fig. 1(a)] along the wave vector at ω is

$$\Delta k(\Omega,\alpha,D,\theta) = k_\mathrm{o}(\omega+\Omega)\cos(D\Omega) + k_\mathrm{o}(2\omega)\cos(\alpha) - k_\mathrm{e}(3\omega+\Omega,\theta)\cos\left[\beta(\Omega,\alpha,D,\theta)\right], \tag{1}$$

where α is the internal noncollinear angle between the 1ω and 2ω beams, θ is the frequency-dependent angle between the crystal axis and the wave vector at $3\omega + \Omega$, and β is the frequency-dependent angle between 1ω and $3\omega + \Omega$ beams. There is a continuum of combinations of the three degrees of freedom (D, α, and θ) that cancels the phase mismatch and its frequency derivative at $\Omega = 0$, therefore yielding broadband SFG. For example, operation with $\alpha = 1.7°$ and $\Delta = -0.59$ mrad/nm ($\Delta = -2\pi cD/\lambda^2$) in a Type-I KDP crystal allows for the conversion of ~10 THz of bandwidth from 1053 nm to 351 nm in a 1-cm crystal, i.e., 10× larger than in a collinear scheme [Fig. 1(b)]. Crystal-angle detuning allows for SFG of frequency components symmetrically located relative to 1ω, e.g., the signal and idler resulting from parametric amplification of a 1ω signal close to spectral degeneracy with a pump at 2ω (Ref. 5).

The SFG demonstration follows the principle described in Fig. 1(a). A collinear optical parametric amplifier (OPA) seeded with either a monochromatic tunable signal or a spectrally incoherent signal originating from an amplified spontaneous emission source at wavelengths below 1053 nm is pumped by a 1.5-ns pulse at 526.5 nm, leading to a combined signal and idler symmetric relative to 1053 nm (Ref. 5). The OPA 1ω output is spectrally dispersed by an 802.5-l/mm transmission grating at Littrow, which is re-imaged onto a 1-cm KDP crystal, itself re-imaged onto a 2305-l/mm transmission grating that compensates for the 3ω angular dispersion resulting from the 1ω angular dispersion and noncollinear SFG geometry. The OPA 2ω pump is separately re-imaged to the SFG crystal. For the fixed 1ω angular dispersion D, the noncollinear angle α is optimized for frequency conversion of a

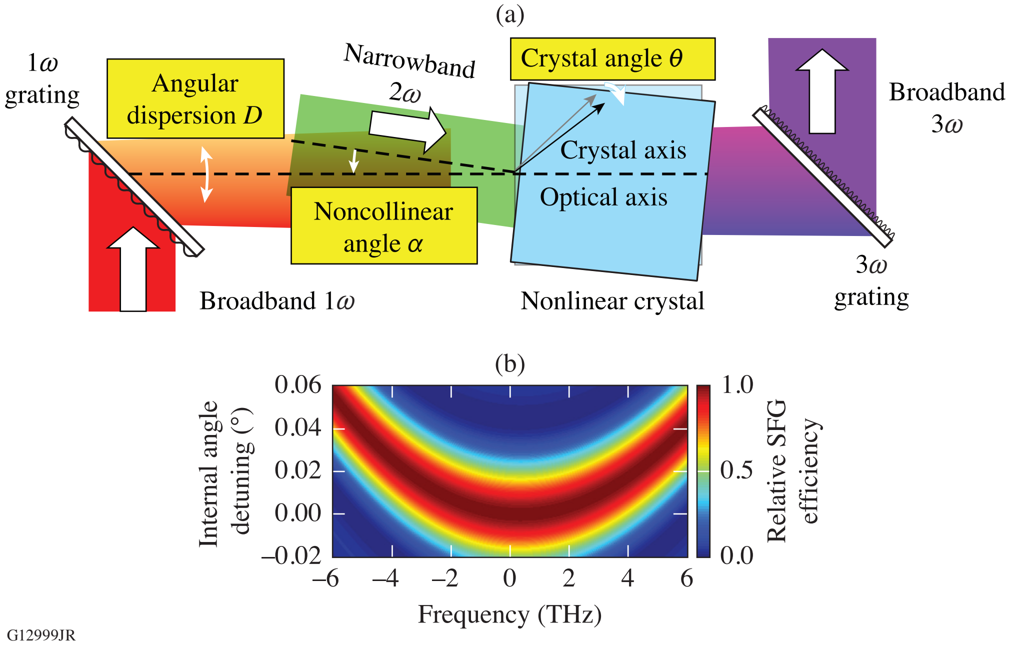

Figure 1
(a) Sum–frequency generation of a broadband angularly dispersed 1ω pulse with a narrowband 2ω pulse in a noncollinear geometry; (b) relative SFG efficiency for $\alpha = 1.7°$ and $\Delta = -0.59$ mrad/nm versus crystal angle detuning.

monochromatic signal at 1030 nm and the corresponding idler at 1077 nm at the same crystal angle, therefore ensuring symmetric phase matching relative to 1053 nm.

The spectral acceptance measured with a monochromatic tunable 1ω OPA seed shows that noncritical SFG is obtained at one specific crystal angle, while detuning matches the SFG to a pair of signal and idler beams at opposite frequencies relative to 1ω [Figs. 2(a) and 2(b)], in excellent agreement with the simulations [Fig. 1(b)]. Broadband spectrally incoherent light at 1ω is obtained by seeding the OPA with an amplified spontaneous emission pulse covering ~10 nm at 1030 nm. With the combined signal and idler, SFG-crystal tuning allows for the generation of more than 10 THz of bandwidth either centered at 351 nm or in two symmetric side lobes, depending on the crystal angle (Fig. 3).

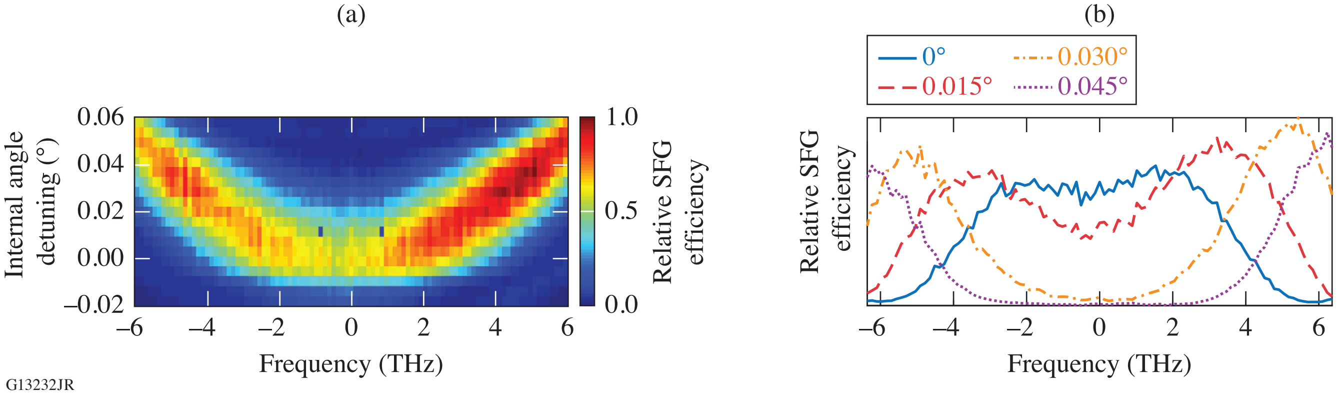

Figure 2
Spectral acceptance characterization of a 1-cm KDP crystal with a tunable monochromatic 1ω signal: relative SFG energy versus (a) frequency relative to 3ω and crystal angle and (b) lineouts at four crystal angles.

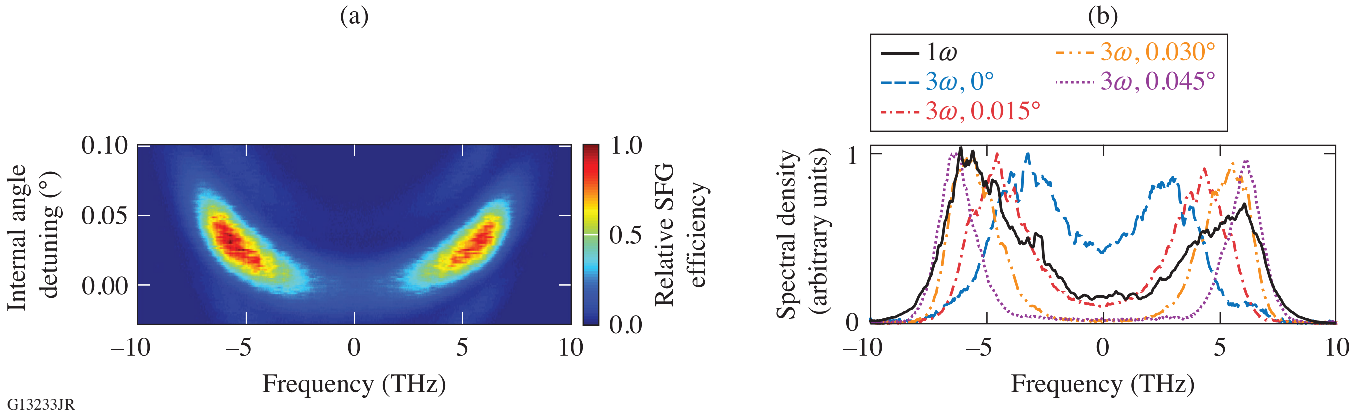

Figure 3
Spectral density of a generated broadband spectrally incoherent pulse at 3*ω* (a) as a function of crystal angle and (b) for four crystal angles. In (b), the spectral density of the 1*ω* input to the SFG stage is plotted with a black line.

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