Frequency doubling of femtosecond erbium-fiber soliton lasers in periodically poled lithium niobate

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We report efficient frequency doubling of passively mode-locked femtosecond erbium-fiber lasers. Quasi-phase-matched second-harmonic generation in periodically poled lithium niobate is used to generate 8.1 mW of 190-fs (FWHM), 90-pJ pulses at 777 nm with a conversion efficiency greater than can be obtained with existing birefringently phase-matched nonlinear materials. A dispersion-compensation-free soliton oscillator generating transform-limited 230-fs (FWHM) pulses at 1554 nm is used as a pump laser. © 1997 Optical Society of America

Diode-pumped passively mode-locked erbium-doped-fiber lasers (EDFL's) are compact and flexible sources of femtosecond pulses. In contrast to bulk femtosecond lasers, erbium-fiber lasers do not require bulk dispersion-compensating elements (because of the soliton pulses that they support), permit the stable generation of picojoule, femtosecond pulses at low and adjustable repetition rates (<5 MHz–2 GHz),[1] and can be operated with broad-area diode pumps.[2] Two requirements for making fiber lasers attractive for many applications in ultrafast optics that currently rely on Ti:sapphire lasers are pulse energy and wavelength. Chirped pulse amplification techniques have been used to generate nanojoule and microjoule energies in all-fiber[3] and hybrid[4] systems, respectively. Because erbium lasers can produce femtosecond pulses in the wavelength range 1530–1610 nm,[5] frequency doubling can be used to reach 765–805 nm.

Commercial doubled EDFL's with output energies in the picojoule range are entering the market; however, these systems are limited by the low second-harmonic-generation (SHG) conversion efficiencies obtained with conventional nonlinear materials. Lenz *et al.*[6] reported a high-energy (1.8-nJ) externally compressed stretched-pulse EDFL doubled in critically phase-matched β-barium borate (BBO) generating 73-fs second-harmonic pulses with a 5% efficiency.

To improve on this efficiency, quasi-phase-matched (QPM) SHG[7] can be used to provide noncritical phase matching anywhere within a material transparency range while using the material's highest nonlinear coefficients. The advantages of QPM SHG in the picosecond regime have been demonstrated by Pruneri *et al.*[8]

Here we report QPM doubling of femtosecond pulses by using a diode-pumped erbium soliton oscillator and bulk periodically poled lithium niobate (PPLN). Internal conversion efficiencies of 25% were obtained, and 190-fs, 90-pJ pulses with no observable pedestal at 777 nm were generated. These pulses are 2 orders of magnitude more energetic than required (<1 pJ) for injection seeding of femtosecond regenerative amplifiers.[9]

With QPM SHG the phase mismatch between the nonlinear polarization and the free second-harmonic field is reset every coherence length, l_c, by periodic modulation of the nonlinear susceptibility of the medium (termed periodic poling in the case of ferroelectrics) with a period $\Lambda = 2l_c$. For QPM SHG the required grating period (with the grating vector and the incident beam both perpendicular to the surface of the crystal) is given by[5] $\Lambda_{\mathrm{QPM}} = \lambda/2(n_{\lambda/2} - n_\lambda)$, where λ is the fundamental wavelength and n_λ is the refractive index at wavelength λ. The time-averaged efficiency η for undepleted-pump SHG can be expressed as[10]

$$\frac{\eta}{P_\lambda} = \frac{16\pi^2}{\epsilon_0 c}\frac{d_{\mathrm{eff}}{}^2 L}{n_\lambda n_{\lambda/2}\lambda^3} gh\,, \tag{1}$$

where d_{eff} is the effective material nonlinear coefficient ($d_{\mathrm{eff}} = 2d_{33}/\pi = 16.5$ pm/V for QPM SHG in lithium niobate), L is the interaction length, and P_λ is the peak fundamental power. The factor h is a dimensionless coefficient that quantifies the effects of focusing and birefringence on the SHG efficiency and is of the order of unity near optimal focusing for noncritically phase-matched interactions.[8] The factor g accounts for the time dependence of the conversion efficiency and for group-velocity walk-off (spectral narrowing) effects.[11] The decoupling of spatial and temporal effects (treating g and h as independent factors) in Eq. (1) is appropriate if the interaction occurs in the quasi-static or the near-field limit or in both.

The characteristic device length for which the FWHM spectral acceptance of the SHG process equals the pulse bandwidth is given by

$$L_{\max} = \frac{0.44\lambda^2}{\Delta\lambda}\Delta n_g{}^{-1}\,, \tag{2}$$

where $\Delta\lambda$ is the (FWHM) wavelength bandwidth of the pulse and $\Delta n_g = |n_{g,\lambda/2} - n_{g,\lambda}|$ is the group-velocity mismatch parameter, where $n_{g,\lambda} = n_\lambda - \lambda(\partial n_\lambda/\partial\lambda)$ is the group index at wavelength λ. For chirp-free (transform-limited) pulses, Eq. (2) reduces to the group-velocity walk-off length, $L_\tau = k\tau c\Delta n_g{}^{-1}$, where

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τ is the FWHM pulse duration and $k = 1.4$ for sech^2 pulses. In the quasi-static limit ($L < L_{\max}$), g is

$$g = \left[\int_{-\infty}^{\infty} P(t)^2 \mathrm{d}t \right]^2 \bigg/ \left[\int_{-\infty}^{\infty} P(t) \mathrm{d}t \right]^2 , \qquad (3)$$

where $P(t)$ is the time-dependent pulse power; for sech^2 pulses, $g = 0.668$. If $L = L_{\max}$ (as in this experiment), g has a value of 0.32 for sech^2 pulses.

In the nonstationary limit ($L > L_{\max}$) the second-harmonic pulse is lengthened, and g decreases further. As one typically requires that $L \leq L_{\max}$, a material figure of merit (FOM) for noncritically phase-matched SHG of ultrashort pulses can be defined as

$$\text{FOM} = d_{\text{eff}}{}^2/(n^2 \Delta n_g) . \qquad (4)$$

Because QPM interactions are not phase-velocity matched, the group-velocity mismatch is in general larger than that in phase-matched interactions. [Δn_g for 1.56 μm SHG in PPLN, BBO, lithium triborate (LBO), and $LiIO_3$ is 0.089, 0.0029, 0.010, and 0.039, respectively.] However, the larger nonlinear coefficients made available with QPM often more than compensate for the shorter interaction lengths. At 1.56 μm, the FOM is 710, 340, 42, and 12 pm^2/V^2 for PPLN, BBO, LBO, and $LiIO_3$, respectively.

The conversion efficiency for optimally focused SHG with $L = L_{\max}$ is proportional to this FOM for any pulse length, as long as $L_{\max} < L_a$, the aperture length that is due to Poynting vector walk-off.[8] This condition is met for any pulse length in noncritically phase-matched interactions in materials such as PPLN and LBO but is often violated in critically phase-matched interactions in highly birefringent materials such as BBO and $LiIO_3$. For interactions with $L_{\max} > L_a$ the efficiency is proportional not to the FOM but rather to $\text{FOM}\sqrt{L_a/L_{\max}}$ and is therefore pulse-length dependent. Using Eqs. (1) and (2), we find that the small-signal efficiencies of PPLN and LBO-based frequency doublers for 1.56-μm sech^2 pulses with $L = L_{\max}$ and with confocal focusing[10] ($h = 0.8$) are 95%/nJ and 6%/nJ, respectively. Assuming 100-fs FWHM pulses, the efficiencies for BBO- and $LiIO_3$-based doublers are 6%/nJ and 0.6%/nJ, respectively.

In our experiments we used a passively mode-locked erbium-fiber soliton oscillator, pumped with 150 mW (absorbed) of power from a 980-nm master-oscillator power-amplifier diode laser. The 1-m-long fiber was doped with $\sim$1000 parts in 10^6 Er^{3+}. A large core diameter and high output coupling were chosen to keep circulating intensities low enough to minimize undesired nonlinear effects. The laser had a repetition rate of 88 MHz with an average output power of 50 mW.

The pulse spectrum, shown in Fig. 1, had a FWHM of 11.2 nm, with characteristic secondary peaks indicating the presence of a pedestal. Figure 1 (inset) shows the oscillator pulse autocorrelation, indicating approximately sech^2-shaped pulses with FWHM of 230 fs, for a time–bandwidth product of 0.32. The autocorrelation (shown on a log scale) indicates that the pedestal component has low amplitude and therefore cannot contribute appreciably to the SHG process. This pedestal, which was estimated by the technique of Dennis and Duling[12] to contain 14% of the total laser output, can be eliminated by operation at lower output power levels or with a stretched-pulse oscillator[13] containing dispersion-compensating components. However, in this experiment we can tolerate a small pedestal because the SHG process suppresses it at the second-harmonic wavelength, generating high-quality pulses while retaining a simple overall system.

The 18.75-μm-period PPLN sample was fabricated by electric field poling[14] of a 0.5-mm-thick z-cut wafer of congruent lithium niobate. The laser output was focused with an achromatic doublet through a 1.1-mm-long sample to a ($1/e$ electric field radius) spot of 10 μm (measured). The crystal was held at 80 °C to eliminate small amounts of photorefractive damage observed at room temperature. All optical components, apart from the PPLN crystal and the doublet, were antireflection coated for the fundamental or second-harmonic wavelength as appropriate. Of the 50-mW output of the oscillator, 37 mW was delivered inside the PPLN crystal. Average powers were measured with a calibrated germanium photodiode before the doublet for the fundamental and with a calibrated silicon photodiode after the crystal for the harmonic.

The spectrum of the frequency-doubled pulses, shown in Fig. 2, had a FWHM of 4.7 nm; their autocorrelation, shown in Fig. 2 (inset), implies a FWHM of 190 fs, giving a time–bandwidth product of 0.44. Modeling of the spectrum and the autocorrelation of the frequency-doubled pulses by the nonstationary-SHG theory of Akhamanov *et al.*[11] indicates that their pulse shape was transformed from sech^2 to approximately Gaussian because of nonnegligible group-velocity walk-off ($L = L_{\max}$).

The average conversion efficiency was measured as a function of average power (adjusted with a wave plate–polarizer variable attenuator) in the PPLN crystal and is shown in Fig. 3. The small-signal internal conversion efficiency (obtained by accounting for reflection losses at the PPLN and the doublet surfaces) observed

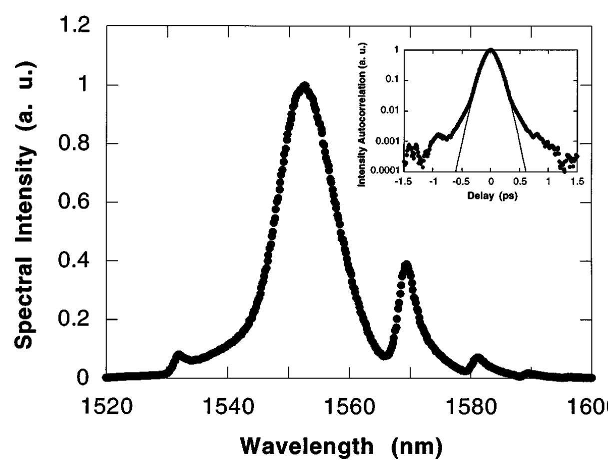

Fig. 1. Fundamental pulse spectrum shown on a linear scale and (inset) autocorrelation shown on a logarithmic scale. The solid curve represents the theoretical autocorrelation of a pedestal-free sech^2 pulse with $\tau_{\text{FWHM}} = 230$ fs.

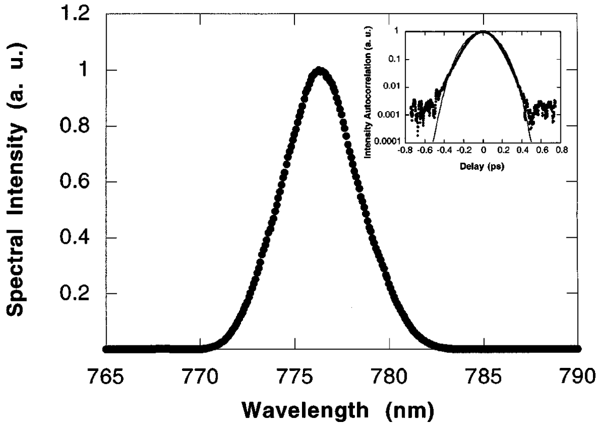

Fig. 2. Second-harmonic pulse spectrum shown on a linear scale and (inset) autocorrelation shown on a logarithmic scale. The solid curve represents the theoretical autocorrelation of the second harmonic of the pulse in Fig. 1 generated in a crystal with $L = L_{\max}$.

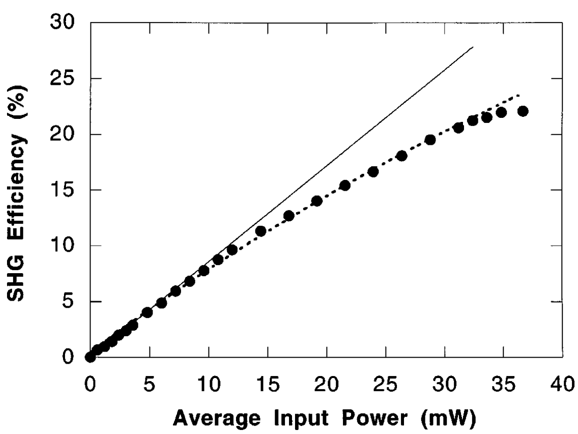

Fig. 3. Internal SHG conversion efficiency plotted against internal average power at 1.56 μm. The solid curve represents the small-signal conversion efficiency of 1.0%/mW. The dashed curve was obtained by radial and temporal averaging of the theoretical output intensity approximated at each radius and time by the plane-wave expression for depleted-pump cw SHG.

was 0.77%/mW. The maximum second harmonic observed, for 37-mW internal pump power, was 7.0 mW for an internal efficiency of 22% and corresponded to 8.1 mW of power generated inside the crystal. As the low-amplitude pedestal is useful neither for most applications that require the fundamental wavelength nor for SHG, only the energy content (~86% of the total) in the ultrashort pulse itself is relevant. Therefore the internal small-signal and maximum conversion efficiencies of fundamental pulse energy, excluding the pedestal component, to harmonic pulse energy were 1.0%/mW (85%/nJ) and 25%, respectively. The small-signal efficiency predicted by Eq. (1) with the peak-to-average power ratio of 40 W/mW is 1.1%/mW (95%/nJ); the 10% discrepancy between the observed and the predicted efficiency is consistent with the imperfect domain structure of the PPLN sample used and experimental error. The 25% average efficiency observed is high enough that the temporal and the spatial peaks of the pulse experienced pump depletion, as is evident in the slight efficiency saturation displayed in Fig. 3. Using 400-μm-long samples of PPLN (30-nm bandwidth), we have observed SHG of 80-fs pulses with comparable efficiencies.

The frequency-doubled source of Ref. 6, with 5% conversion efficiency, achieved a normalized efficiency of ~3%/nJ in a 1-cm-long BBO crystal. With this pump source and a 300-μm-long PPLN crystal the conversion efficiency would have significantly exceeded 50%, limited by details of pump depletion and the recompressed pulse properties.

In conclusion, we have demonstrated frequency doubling of femtosecond pulses with periodically poled $LiNbO_3$. Owing to the large nonlinear coefficient and noncritical phase matching made available with QPM, 25% pulse-energy conversion efficiency is possible with a low-power diode-pumped erbium-fiber soliton laser. Because of the short pulses, near-IR wavelengths and, when frequency-doubled erbium-fiber lasers are combined with EDFA's, the potential for microjoule energy generation, frequency-doubled erbium-fiber lasers promise to be an attractive diode-pumped alternative to workhorse solid-state ultrafast sources.

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