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) 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 picosecond, femtosecond pulses at low and adjustable repetition rates (<5 MHz–2 GHz), and can be operated with broad-area diode pumps. 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 obtained with conventional nonlinear materials. Lenz et al.1 reported 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.

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

\[ L_{\text{max}} = \frac{0.44 \Delta \lambda}{\Delta n_g}, \]

where \( \Delta \lambda \) is the (FWHM) wavelength bandwidth of the pulse and \( \Delta n_g = |n_g,\lambda/2 - n_g,\lambda/2| \) is the group-velocity mismatch parameter, where \( n_g,\lambda = n_\lambda - \lambda (\partial n_\lambda / \partial \lambda) \) is the group index at wavelength \( \lambda \). For chirp-free (transform-limited) pulses, Eq. (2) reduces to the group-velocity walk-off length, \( L_r = k \tau c \Delta n_g^{-1} \), where
\( \tau \) is the FWHM pulse duration and \( k = 1.4 \) for sech\(^2\) pulses. In the quasi-static limit \( (L < L_{\text{max}}) \), \( g \) is

\[
g = \left[ \int_{-\infty}^{\infty} P(t)^2 dt \right]^{2} \left/ \left[ \int_{-\infty}^{\infty} P(t) dt \right] \right. , (3)
\]

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

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

\[
\text{FOM} = \frac{d_{\text{eff}}^2}{(\pi^2 \Delta n_g)} . (4)
\]

Because QPM interactions are not phase-velocity matched, the group-velocity mismatch is in general larger than that in phase-matched interactions. \( |\Delta n_g| \) for 1.56 \( \mu \)m 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 \( \mu \)m, the FOM is 710, 340, 42, and 0.668 \( \mu \)m\(^2\) for PPLN, BBO, LBO, and LiIO\(_3\), respectively.

The conversion efficiency for optimally focused SHG with \( L = L_{\text{max}} \) is proportional to this FOM for any pulse length, as long as \( L_{\text{max}} < L_0 \), the aperture length that is due to Poynting vector walk-off. 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 \( L_{\text{max}} > L_0 \) the efficiency is proportional not to the FOM but rather to \( FOM (L_0/L_{\text{max}}) \) 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-\( \mu \)m sech\(^2\) pulses with \( L = L_{\text{max}} \) and with confocal focusing\(^{13} \) (\( h = 0.8 \)) 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-\( \mu \)m-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 \( \mu \)m (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 Akhanian et al.\(^{11} \) indicates that their pulse shape was transformed from sech\(^2\) to approximately Gaussian because of nonnegligible group-velocity walk-off \( (L = L_{\text{max}}) \).

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

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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.
the pulse experienced pump depletion, as is evi-

The 25% average efficiency observed is high

structure of the PPLN sample used and experimental
efficiency is consistent with the imperfect domain
crepancy between the observed and the predicted
of 40 W

pulse energy were 1.0%

energy, excluding the pedestal component, to harmonic
conversion efficiencies of fundamental pulse en-
Therefore the internal small-signal and maximum
total) in the ultrashort pulse itself is relevant.

was 0.77%/mW. The maximum second harmonic ob-
erved, 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. There-
fore the internal small-signal and maximum conversion efficiencies of fundamental pulse en-
ergy, excluding the pedestal component, to harmonic
pulse energy were 1.0%/mW (85%/nJ) and 25%, re-
spectively. 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% dis-
crepancy 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 evi-
dent 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% con-
version 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%, lim-
ited by details of pump depletion and the recompressed
pulse properties.

In conclusion, we have demonstrated frequency dou-
bling of femtosecond pulses with periodically poled
LiNbO₃. 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 com-
combined with EDFA’s, the potential for microjoule en-
ergy generation, frequency-doubled erbium-fiber lasers
promise to be an attractive diode-pumped alternative
to workhorse solid-state ultrafast sources.

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