Frequency Doubled Er/Brillouin All-Fiber Laser

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25 mW output power Er/Brillouin oscillator and a periodically poled optical fiber with a quasi phase matching resonance at ~1.56 µm are the simplest way to realize nanosecond, all-fiber laser sources operating at ~778 nm and ~389 nm. 25 W peak power pulse train generated at ~778 nm with 120 mW diode pumping is reported.

Introduction

Nanosecond pulse laser sources with extended wavelength diversity are of great interest for numerous applications. The use of fiber lasers for second harmonic generation allows combining efficient wavelength conversion with the possibility to keep all-fiber format. Second-order nonlinear optical processes can be implemented in all-fiber configurations by using a periodically poled fiber as second-order nonlinear medium with quasi-phase-matching [1,2] and a fiber laser as pump source. In the past, second-harmonic generation (SHG) was demonstrated in periodically poled fibers using solid-state lasers [1, 3] or master-oscillator-power-amplifier (MOPA) configurations as pump sources [4]. In order to fully exploit the advantages of all-fiber configurations (low-cost, robustness, compactness, flexibility) and to optimize nonlinear wavelength conversion processes in the periodically poled silica fiber (PPSF), a fiber laser with appropriate characteristics is needed. The requirements for the fiber laser (to be used as pump source for e.g. SHG) are as follows: 1) it must deliver high-peak power pulses in order to obtain high conversion efficiency of the pump; and 2) its optical spectrum must be located inside the quasi-phase-matching (QPM) resonance band of the PPSF, which is about ~1 nm for a 10 cm long device. A self-Q-switched erbium fiber laser employing stimulated Brillouin scattering (SBS) [5] can potentially meet all these requirements and, moreover, can bring simplicity of configuration and possibility of wavelength tuning. Providing a typical recovery time for the population inversion in the doped fiber as long as hundreds of microseconds (i.e. the repetition rate as low as several kHz) such lasers are able to emit nanosecond pulses with record values of the peak/average power contrast ranging up to ~10^5 that makes them very efficient for nonlinear conversion in fibers [6].

Here we present a low-cost solution for all-fiber frequency-doubled laser sources by combining two ingredients: 1) a self-Q-switched erbium/SBS fiber laser that generates ~5 ns pulses with a bandwidth of ~0.25 nm and a peak/average power contrast up to ~1 kW/25 mW; and 2) a periodically poled fiber with QPM resonance around ~1556 nm. We demonstrate that, in spite of the low average power (~250 µW) associated with the random nature of erbium/SBS laser pulsation [5], the peak power of second-harmonic pulses at ~778 nm lies within the ten-watts-scale and is high enough to generate the fourth harmonic at ~389 nm in a cascade process. In practice, simple bending of fiber allowed us to completely suppress the residual pump and to select the second and fourth harmonic signals. The advantage of the proposed solution relies in the specific suitability of the nanosecond pulses generated through the multi-cascade SBS process for nonlinear interaction. Since the optical spectrum of the pulses contains several SBS components (the SBS shift is ~11 GHz) locking between them could considerably enhance values of peak power available for SHG.

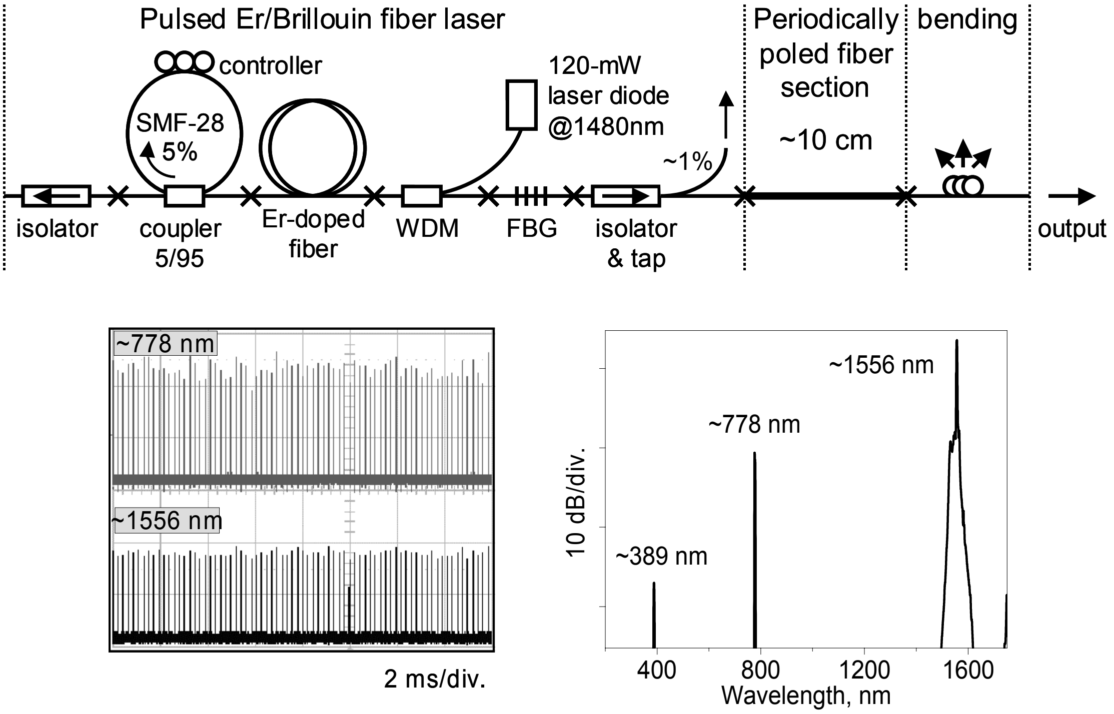

Fig.1. Configuration of the all-fiber frequency-doubled laser source(a).
Typical oscilloscope traces (b) and an optical spectrum (c) recorded with the laser.

Experimental setup

The scheme of the frequency doubled Er/Brillouin laser is shown in Fig.1(a). The all-fiber format of the configuration is maintained by direct splicing of standard low-cost telecom components. The configuration is pumped by a 120-mW laser diode at ~1480 nm. The Er/Brillouin oscillator [5] generates a pulse train with a repetition rate of ~4 kHz (Fig.1(b)). Most of the laser intensity is emitted through few SBS components localized near the Stokes side of the FBG reflection spectrum within ~0.25 nm (see Fig.2(a)). A ~40-GHz-bandwidth FBG used in the cavity sets the fundamental laser frequency precisely at ~1556.25 nm, which is close to the QPM resonance peak of the periodically poled fiber. The ~10-cm long PPSF was fabricated from a twin-hole fiber by point-to-point UV-erasure of the second-order nonlinearity induced by uniform thermal poling (T=250 ^{o}C, ~30 minutes with ~4 kV applied). The fiber geometry, the poling and erasure parameters were described in ref. [2]. The fiber laser is fusion spliced to the PPSF and the laser polarization is optimized in order to get the maximum SH power. The splice between the twin-hole fiber and the SMF28 is not optimized and estimated to be around ~3 dB, thus reducing the input fundamental average/peak power in the poled fiber to about ~12 mW / 500 W. Gigantic pulses initiated through multi-cascade SBS induce second-harmonic generation in the periodically poled fiber around the QPM resonance.

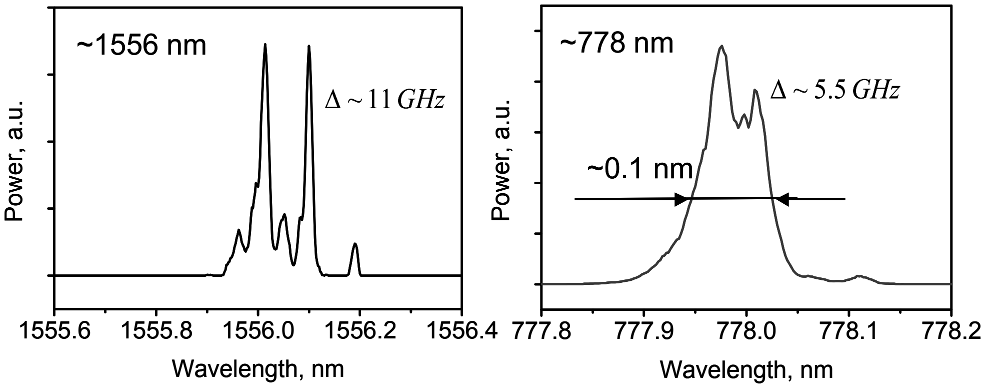

Fig.2. Typical optical spectra of the fundamental (a) and SH (b) radiation.

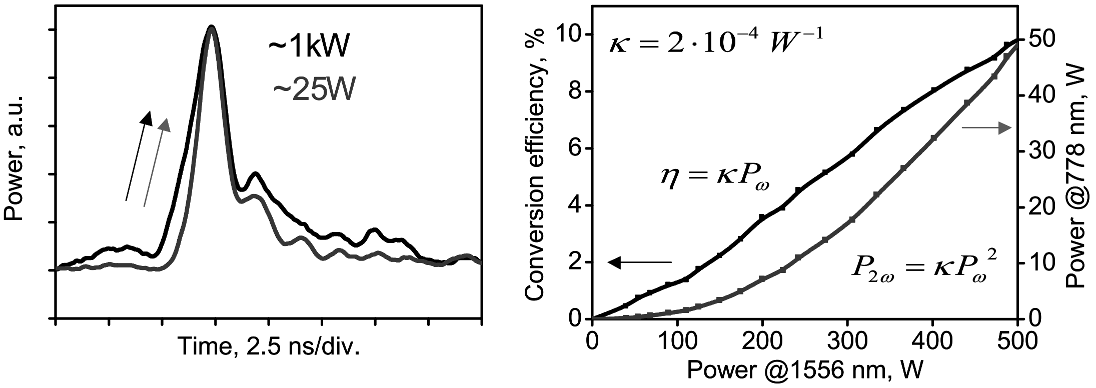

Fig.3. Typical oscilloscope traces of the fundamental (black) and SH (grey) pulses (a). Conversion efficiency (black) and SH pulse peak power (grey) as dependences on the fundamental pulse peak power (b). The dependencies (b) are calculated from the oscilloscope traces (a).

Results and discussion

A typical optical spectrum of the output radiation covering almost the full range of the optical spectrum analyzer is shown in Fig. 1(c). One can see that not only the second harmonic is generated but also the fourth harmonic. Whereas the former originates from QPM of the fundamental radiation, the latter is likely to be due to SHG of the former through modal phase matching. Fine structures of the spectral lines at 1556 nm and 778 nm are shown in Fig. 2. Both structures exhibit clear signatures of the stimulated Brillouin scattering that is the origin of the laser operation. Whereas the Brillouin laser generates two spectral peaks with the spacing of ~11 GHz (that is the Brillouin shift) the SHG results in two peaks with the spacing of ~5.5 GHz (that is half of the Brillouin shift). All presented spectra were recorded with an optical spectrum analyzer Ando AQ-6317B operating in a pulse low-pass-filter (LPF) mode (the filter time constant is ~2 ms).

Typical pulse trains generated at ~778 and ~1556 nm are shown in Fig. 1 (b). Since the first train is a result of the frequency doubling of the second train, it exhibits slightly larger fluctuations of the pulse amplitude. Insight into the dynamics of the SHG process was obtained by attenuating the radiation emitted by the source and by detecting it using two fast photodiodes. The laser pulses were registered simultaneously from the main output (SH pulses) and from the ~1% tap (pump pulses). The bandwidths of registration channels are ~1 GHz. Typical oscilloscope traces of pump and SH pulses are shown in Fig. 3(a). One can see that the SH pulse is narrower than the pump pulse. Besides, the Fig. 3(b) shows that for the reported operation the SH power is precisely proportional to the square of the pump power $P_{2\omega} = \kappa P_{\omega}^{2}$ (see, Fig. 3(b)), as it usually takes place with SH generation. The maximal SH average power was ~250 μW corresponding to ~25 W SH peak power, and resulting in a peak conversion efficiency of $\eta = \kappa P_{\omega}$ ~10% inside the PPSF. Further increase of the conversion efficiency exceeding ~50% could be ensured by using longer PPSF and optimization of the splice loss.

Conclusion and acknowledgements

The proposed configuration offers simple solution for all-fiber frequency-doubled laser sources. The solution opens the potential to produce nanosecond pulses through the complete visible spectrum employing as a pump the rare-earth doped fiber lasers commonly operating in the infrared. Owing to the low chromatic dispersion, the periodically poled silica fiber used in our configuration had a QPM bandwidth of about ~1 nm for a ~10 cm long device (10 times larger than in typical nonlinear crystals such as $LiNbO_3$). The Brillouin lasers delivering ns pulses with the linewidth less than ~0.25 nm will be suitable for frequency doubling up to ~50 cm interaction lengths. Therefore, an increase of the conversion efficiency above 50% may be achieved by utilizing the total available power budget for the fiber laser in conjugation with the use of long PPSF. Additional advantages of such sources are compactness, robustness, low cost and their all-fiber integrated format.

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