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# 1 GHz Femtosecond Erbium-doped Fiber Lasers

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**Abstract:** Saturable Bragg reflector (SBR) mode-locked Er-doped fiber lasers around 1550 nm with a repetition rate of 1 GHz are demonstrated. Key steps to obtain stable, femtosecond pulses by avoiding thermal damage of the SBR are discussed.

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**OCIS codes:** (140.3280) Laser amplifiers; (140.3500) Lasers, erbium; (320.7090) Ultrafast lasers

## 1. Introduction

High repetition rate sources with femtosecond laser pulses enable numerous applications like optical arbitrary waveform generation [1], frequency metrology [2] and high speed optical sampling [3]. To build compact fiber laser cavities, passive mode-locking with a saturable Bragg reflector (SBR) [4], [5] combined with soliton pulse shaping [6] has proven a successful approach. However, when scaling fiber lasers towards higher repetition rates, thermal damage regulation becomes more crucial for long-term stable operation. Recent experimental demonstrations of fiber lasers with SBRs have achieved repetition rates as high as 3 GHz [7]. However, thermal damage of the SBR, ultimately limited the long-term stability of the mode-locked output. By butt-coupling the gain fiber directly to the SBR, intense thermal heating can be introduced at the SBR's surface so that these lasers tend to fail after a brief period of operation. Stable fiber lasers up to 2 GHz using SBRs were shown by McFerran et al. [8] that operate in the picosecond pulse regime. Therefore, in the following, we will present two approaches to form stable soliton femtosecond laser sources that specifically address and resolve the thermal damage challenge.

## 2. Experimental Results and Discussion

The experimental set-up of an Er-doped fiber laser is shown in Fig. 1(a). The laser's linear cavity consists of 83 mm of Liekki Er80-8/125 gain fiber with anomalous dispersion of  $-20 \text{ fs}^2/\text{mm}$ . The fiber is butt-coupled to a 5% dielectric-coated output coupler on one end and imaged onto a SBR at the other end to avoid direct contact of the hot fiber core to the SBR. Due to this intracavity free space section and its higher intrinsic losses, a SBR with a modulation depth of 21% (commercially available by BATOP GmbH), a 2-ps relaxation time constant and a saturation fluence of  $20 \mu\text{J}/\text{cm}^2$  was used.

The laser mode-locks with 2-pJ pulses at a fundamental repetition rate of 1.047 GHz. The optical spectrum of the output pulse train [see Fig. 1(b)] shows that the pulses are centered around 1559 nm and have a 3-dB bandwidth of 5.0 nm, corresponding to transform-limited pulse durations of 510 fs assuming a  $\text{sech}^2$ -shape. The RF spectral trace shows the repetition rate and its harmonics up to 10 GHz [Fig. 1(c)] with a signal to noise suppression ratio of 40 dBm and, thus, confirms the laser's stable operation in a fundamentally mode-locked state. Currently, the laser performance is limited by the pump power provided from one 980-nm diode that couples approximately 200 mW into the gain fiber.

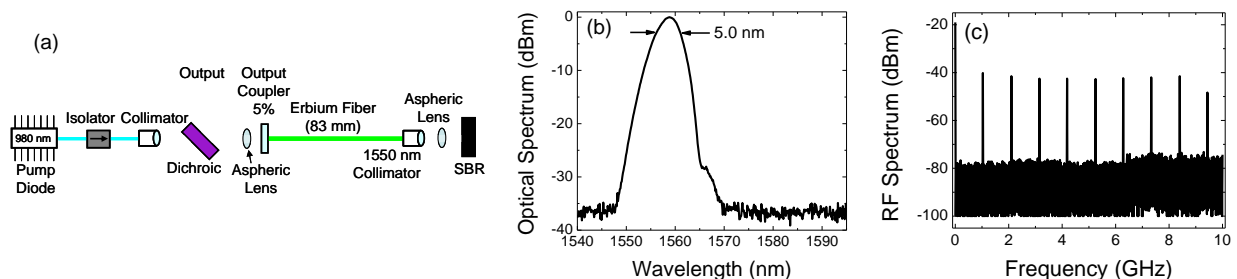


Fig. 1. (a) Experimental set-up of Er fiber laser with a free space section; (b) Optical spectrum centered at 1559 nm with a 3-dB bandwidth of 5.0 nm; (c) RF spectrum with fundamental repetition rate of 1.047 GHz for a resolution bandwidth of 100 kHz.

Another approach to spatially separate the gain fiber from the SBR surface is shown in Fig. 2(a). A 5-mm long piece of standard single-mode fiber (SMF-28e) is spliced to a 97-mm Er gain fiber (Liekki Er80-8/125) and is butt-

coupled between a 10% output-coupler and a SBR. A III-V semiconductor SBR with a 2.5% modulation depth, a saturation fluence of  $25 \mu\text{J}/\text{cm}^2$  and a recovery time of 6 ps was designed, fabricated and characterized. To reduce the absorption of the residual pump power and thus the localized heating, a pump-reflecting dielectric coating was deposited onto the SBR. In addition, the SBR substrate was thinned down from  $350 \mu\text{m}$  to  $150 \mu\text{m}$  and soldered with indium onto a copper block to lower the thermal resistance. The thinned SBR substrate, the pump-reflective coating and the additional SMF piece proved sufficient heat sinking to prevent any SBR damage. Thus, with these key steps, the thermal damage issues were overcome and mode-locked operation was obtained continuously over multiple days.

This laser produced an optical spectrum centered at  $1565.5 \text{ nm}$  with a full width at half maximum bandwidth of  $12.4 \text{ nm}$ , corresponding to 208-fs duration solitons, at a fundamental repetition rate of  $986.25 \text{ MHz}$ . Fig. 2 shows these results. The average output power emitted by this cavity is  $20.8 \text{ mW}$ , corresponding to 21-pJ pulses, while being pumped with  $730 \text{ mW}$  of  $977 \text{ nm}$  light delivered by polarization combined pump diodes.

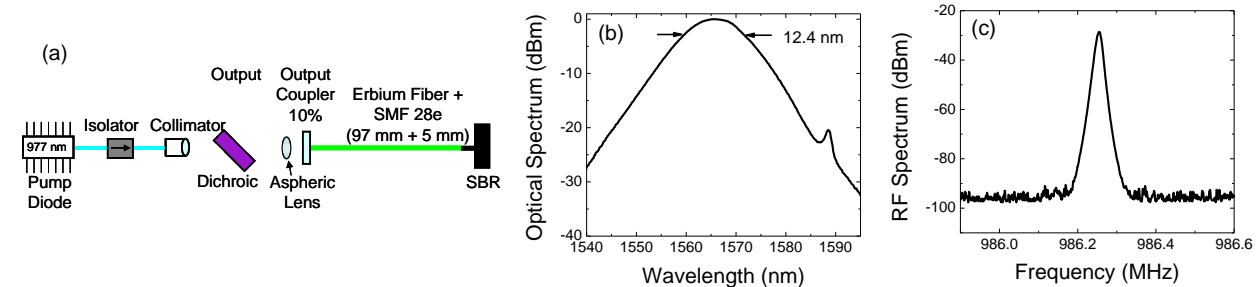


Fig.2. (a) Schematic of butt-coupled 1 GHz Er gain with SMF fiber laser; (b) Optical spectrum centered at  $1565.5 \text{ nm}$  with a 3-dB bandwidth of  $12.4 \text{ nm}$ ; (c) RF spectrum with fundamental repetition rate of  $986.25 \text{ MHz}$  for a resolution bandwidth of  $10 \text{ kHz}$ .

Both laser set-ups are compact, self-starting and allow turn-key operation. The SBR-butt-coupled configuration generates shorter femtosecond pulses with higher output energy due to reduced intracavity losses and a higher output coupling ratio. Its repetition rate is determined by the length of the gain fiber with a small tuning range possible by thermally tuning or mechanically stretching of the fiber. The laser with the free-space section allows for an exact tuning to a desired repetition rate through varying the length of the free-space part, at the cost of higher intracavity losses.

### 3. Conclusion

We presented two approaches to overcoming thermal damaging of SBRs in high repetition rate laser cavities caused by butt-coupling the gain fiber directly to the SBR. One laser configuration included a free space section between the end of the gain fiber and the SBR. The laser produced an optical spectrum with a 3-dB bandwidth of  $5.0 \text{ nm}$  at  $1559 \text{ nm}$  for a repetition rate of  $1.047 \text{ GHz}$ . In addition, we demonstrated lasing with an Er-gain fiber spliced to a short piece of SMF fiber to isolate the gain fiber core from the SBR. The fiber assembly is butt-coupled to a thinned SBR with a pump-reflecting coating for good thermal conduction. This self-starting mode-locked oscillator generates optical pulses with transform-limited durations of 208 fs with an average output power of  $20.8 \text{ mW}$  at  $986.25 \text{ MHz}$ . These stable, compact and femtosecond fiber laser oscillators at  $1 \text{ GHz}$  pave the way to generating femtosecond pulses at even higher repetition rates.

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