Broad multiwavelength source with 50 GHz channel spacing for wavelength division multiplexing applications in the telecom C band

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We present a multiwavelength source with a spectral width of 42 nm at −20 dB. The frequency comb is generated by spectrally broadening the output of an amplified 50 GHz Er:Yb:glass laser with a highly nonlinear photonic crystal fiber. After spectral flattening the comb covers 37 channels with 5.4 mW average power per channel, and locking only one central wavelength channel to the International Telecommunication Union grid results in a maximum frequency error of 0.24% for all channels. © 2008 Optical Society of America

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Current wavelength-division-multiplexing (WDM) networks typically rely on large banks of fixed cw distributed feedback (DFB) lasers. Each single DFB laser acts as an optical source for a single wavelength channel, requiring dedicated wavelength control, thermal management, and drive electronics. This complexity comes at a significant cost. A source emitting at different wavelengths simultaneously would considerably reduce the system complexity and the per-channel cost. Among the first multiwavelength sources (MWSs) were passively mode-locked lasers at megahertz repetition rates, employing the scheme of chirped-pulse WDM (CPWDM) [1]. To enhance the channel spacing from the megahertz to the gigahertz level, the scheme of harmonic mode-locking was applied to these fiber lasers [2]. However, both schemes suffered from uneven channel spacing. Multiwavelength lasing has also been demonstrated with semiconductor optical amplifiers (SOAs) or erbium-doped fiber amplifiers (EDFAs) and intracavity comb-generating filters. EDFA approaches [3] usually have a limited channel count owing to limited gain bandwidth. SOA-based ring lasers [4] typically have a higher channel count, but the linewidth of the individual modes is too broad for most applications.

Here we demonstrate an MWS based on a spectrally broadened high-repetition-rate passively mode-locked Er:Yb:glass laser. Compared to other approaches [5], the mode-locking mechanism is entirely passive and requires no high frequency-driving electronics. Through the fundamental mode locking of the laser, instabilities, such as supermode noise and phase drifts, are avoided. These lasers generate an optical comb at the carrier frequency, where the spacing of the individual modes exactly equals the repetition rate. Therefore, pulse-generating lasers (PGLs) naturally qualify as stable MWS. Repetition rates matching the WDM channel spacing are particularly interesting. Every comb line of the MWS can serve as a transmission channel and no spectral power is wasted, as opposed to systems operating at a lower pulse repetition rate (and therefore increased comb density) than the WDM channel spacing. Commercially employed transmission systems usually rely on a channel spacing of 50 or 100 GHz, thereby relaxing the constraints on the selectivity and steepness of the WDM filters. To increase the number of generated channels, the optical comb of the laser can be spectrally broadened with a dispersion-engineered highly nonlinear photonic crystal fiber (PCF). The stability of the broadened spectrum greatly benefits from the near-quantum-limited phase noise characteristics (i.e., very low intensity fluctuations) of high-repetition-rate Er:Yb:glass lasers [6,7].

Diode-pumped passively fundamentally mode-locked solid-state lasers with very high pulse repetition rates [8,9] have received particular recognition as low-noise PGL for telecom applications [10]. Recently, passively mode-locked Er:Yb:glass lasers with repetition rates up to 50 [11] and 90 [12] GHz have been demonstrated. Dense wavelength division multiplexing (DWDM) transmission systems using a broadened 12.5 GHz Er:Yb:glass laser [7] or a broadened actively mode-locked diode laser [13] as MWS were demonstrated. Here we demonstrate an MWS based on a 50 GHz Er:Yb:glass laser, eliminating the wavelength filters needed to convert from 12.5 GHz spacing to 50 GHz and thereby reducing system complexity and cost while increasing overall stability. Such a system can replace a large number of individual laser sources.

The MWS relies on two building blocks, a pulsed laser source and spectral broadening (Fig. 1). A passively mode-locked Er:Yb:glass laser with a repetition rate of 50 GHz serves as the pulse source. The laser is similar to the one described in [11] but with improved mirrors. This resulted is an increased average output power of 12 mW free space (compared to the earlier 7 mW) and 4 mW fiber coupled. The optical bandwidth was 2.2 nm with a pulse duration of 2.0 ps. The center wavelength is 1533 nm, determined by the intrinsic gain peak of Er:Yb:glass and

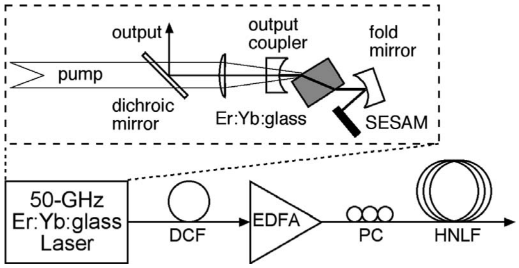

Fig. 1. Experimental setup for the spectral broadening of the 50 GHz comb. DCF, dispersion compensating fiber; EDFA, erbium-doped fiber amplifier; PC, polarization controller; HNLF, highly nonlinear fiber.

therefore very reproducible [14]. A semiconductor saturable absorber mirror (SESAM [15]) is used for passive mode-locking, and the pulsing is self-starting (as opposed to Kerr-lens mode-locking, for example) with excellent long-term reproducibility of the pulse shape [8]. This enables stable comb generation without the need for active monitoring and controlling of its spectral properties.

The equally spaced and comb-shaped optical spectrum of a mode-locked laser has two controllable degrees of freedom: the comb spacing (i.e., channel spacing) f_{rep} and the comb offset given by the carrier envelope offset (CEO) frequency (f_{CEO}) [16,17] $f_n = f_{\mathrm{CEO}} + n f_{\mathrm{rep}}$, where n is the channel number. For WDM applications it is often sufficient to lock only one central wavelength channel f_n (i.e., $\lambda = 1535$ nm, $f_n = 195$ THz, and $n \approx 3900$) to the International Telecommunication Union (ITU) grid by slightly changing the pulse repetition rate with a small cavity length adjustment without any stabilization for the f_{CEO}. For the 50 GHz channel grid, the maximal variation of f_{CEO} is $\delta f_{\mathrm{CEO}} = \pm 25$ GHz, which we can compensate for by adjusting f_{rep} to keep the central wavelength channel locked to the ITU grid $f_n = \delta f_{\mathrm{CEO}} + n(f_{\mathrm{rep}} \pm \delta f_{\mathrm{rep}})$. This leads to a maximum error for the channel spacing of $\delta f_{\mathrm{rep}} \approx \delta f_{\mathrm{CEO}}/n = \pm 6.4$ MHz (i.e., 0.013%) and for the channel frequency of $(N/2)\delta f_{\mathrm{rep}}$ assuming an N-channel comb. In our case we have $N = 37$, resulting in an acceptable error of ≈ 120 MHz (i.e., 0.24%). The full C band ranges from 1530 to 1565 nm and supports 88 channels with 50 GHz spacing, which gives a maximum channel frequency error of 282 MHz (i.e., 0.56%) using this simple stabilization scheme.

For efficient spectral broadening the pulses were amplified with an EDFA to an average power of 530 mW, which corresponds to a pulse energy of 10.6 pJ at 50 GHz. To compensate for the dispersion introduced by the EDFA, the pulses were prechirped with a dispersion-compensating fiber (DCF). With a total dispersion of −0.7 ps/ns we reduced the pulse duration to 1.5 ps (Fig. 2). The pulses were then launched into a 50 m long piece of highly nonlinear PCF (NL-1550-NEG-1 from Crystal Fiber). This fiber is engineered to have a specially flattened dispersion profile [18] with the zero-dispersion wavelength at 1535 nm. The fiber has a high nonlinear coefficient of $\sim 11\ (\mathrm{W\,km})^{-1}$ and is spliced to a standard single-mode fiber via an intermediate fiber piece. The total

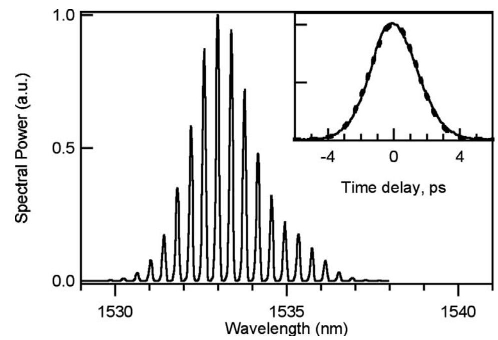

Fig. 2. Optical spectrum of the 50 GHz comb after amplification (linear scale). The optical width is 2.2 nm. The inset shows the measured autocorrelation (solid curve) with a sech^2-fit (dashed curve) corresponding to a 1.5 ps pulse duration.

splicing losses are 0.5 dB. The polarization state in the nonlinear fiber was controlled with fiber polarization controllers.

At a launched power of 530 mW, the output spectrum (Fig. 3) has a width of 16 nm at −3 dB, which is an eightfold increase in optical bandwidth. At −20 dB, the width is 42 nm. The total power in the output spectrum was 320 mW. The inset of Fig. 3 resolves the individual modes of the 50 GHz comb, which extend far above the amplified spontaneous emission background. The optical signal-to-noise ratio is 25 dB in the side lobes around 1540 and 1525 nm and about 30 dB at maximum. The spectra are recorded with a bandwidth of 10 pm, corresponding to 1.3 GHz at 1535 nm. The power distribution of the optical modes in the broadened spectrum was equalized using a dynamic gain equalizer (DGE) from Silicon Light Machines. Its design is spectrally seamless, meaning it can be used for any DWDM signal regardless of channel spacing or bit-rate. The dynamic range is 15 dB with residual spectral ripples in the filter function of less than 0.2 dB (peak-to-peak). The maximum spectral correction slope is 4 dB/nm. As the usable spectral range of this device is limited to the C band, the width of the broadened spectrum is slightly reduced by lowering the amplification of the EDFA. Despite the lower average power, each channel now has more power and a higher optical signal-to-noise ratio. The total average power in the broadened comb was attenuated from 280 to 200 mW, limited by power restrictions of the DGE. We obtained 37 channels with an average power per chan-

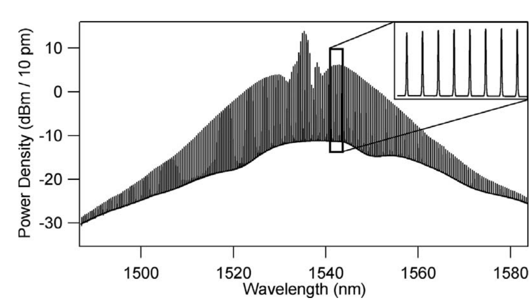

Fig. 3. Measured frequency comb shown on a logarithmic scale. The inset resolves individual lines of the 50 GHz comb.

nel of 5.4 mW (Fig. 4). The flatness was 3.5 dB, limited by the modulations in the center of the frequency comb and typically observed for spectral broadening by self-phase modulation.

In conclusion, we demonstrated a cost-effective method to generate a large number of WDM channels directly with a 50 GHz spacing by exploiting the unique properties of a passively fundamentally mode-locked 50 GHz Er:Yb:glass laser and a highly nonlinear PCF. Compared to the unbroadened spectrum, we could broaden the optical bandwidth by a factor of 8. We demonstrated 37 channels covering 42% of the full C band with an average power per channel of 5.4 mW/channel and a simple ITU channel-locking scheme with a maximum frequency error of 0.24%. The flatness was 3.5 dB. Compared to earlier results [19], the high pulse repetition rate of 50 GHz directly matched typical channel spacing of many commercial transmission systems operating on the ITU grid. Together with the higher channel spacing and the increased number of channels, the bandwidth of the source could be extended by a factor of 3 and now covers 1850 GHz around 1535 nm. Furthermore, the comb generation solely relied on passive mode locking with a SESAM without the need for spectral filtering. The electronic components we are kept to a minimum. Two current sources for the pump diodes of the Er:Yb:glass laser and the EDFA we are sufficient to operate the comb. Such frequency comb generating systems significantly reduce system complexity on the transmission side of WDM networks. The number of laser sources was decreased and among with it the number of supply systems (wavelength control, temperature management, control, and driving electronics). Adding a monolithically integrated multichannel WDM modulator [20] will result in a compact and cost-efficient transmitter for currently installed fiber networks.

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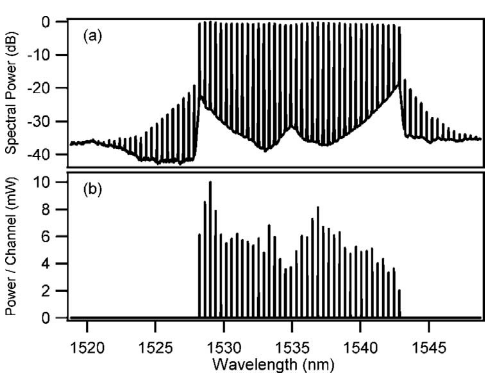

Fig. 4. Measured optical spectrum of the flattened 50 GHz comb: (a) logarithmic scale and (b) linear scale. Average power per channel 5.4 mW, flatness 3.5 dB.

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