Frequency-comb-referenced multi-channel fiber laser for DWDM communication

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Abstract: We propose an all-fiber-based multi-channel optical scheme that enables simultaneous generation of multiple continuous-wave laser wavelengths with stabilization to the frequency comb of a femtosecond laser. The intention is to produce highly stable, accurate wavelength channels with immunity to environmental disturbance so as to enhance the transmission capacity of dense wavelength division multiplexing (DWDM) communications. Generated wavelengths lie over a wide spectral range of 5 THz about 1550 nm, each yielding a narrow linewidth of less than 24 kHz with an absolute position uncertainty of ~2.24 × 10^{-12} (10 s averaging) traceable directly to the atomic Rb clock.

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References and links
1. Introduction

Dense wavelength division multiplexing (DWDM) in fiber-optic communications is intended to increase the transmission capacity by sending as many wavelength channels as possible through a single fiber at a same time [1–3]. The number of wavelength channels within the spectral range of currently available Er-doped fiber amplifiers (EDFA) is determined by the least wavelength spacing required to separate two adjacent channels. Much work has been done to narrow the wavelength spacing to the level of ~100 GHz [4,5], but further reduction is being obstructed by the guard band that has to be inserted between channels to avoid the crosstalk due to the wavelength instability of the lasers in use. For instance, Fabry-Perot laser diodes (FP-LDs) and distributed-feedback diode lasers (DFBs) used for today’s optical communications require guard bands larger than ~20 GHz as their wavelength instability remains in the range of $10^{-6} \text{ to } 10^{-7}$ on the whole [6–8]. In this respect, high wavelength stability is a prerequisite for increasing the number of wavelength channels in optical communications.

The DWDM transmission capacity also depends upon the data transfer rate at each wavelength channel. Quite a few modulation techniques developed for high speed data transfer require contracted linewidth lasers to be used for coherent data transfer and detection. For example, the channel linewidth should be less than 1.6 MHz for the star 16 quadrature amplitude modulation and further below 240 kHz for the 16 phase-shift keying [9]. Thus, light sources for DWDM should be able to provide multiple wavelengths of a narrow linewidth with high stability. In fact, various intra-cavity modulators were devised to generate multiple wavelengths from a single ring-cavity oscillator comprised of an Er-doped fiber as the gain medium [10,11]. This approach is simple to implement but suffer power fluctuation between wavelength channels due to gain competition. Besides, the temporal stability and absolute position of each wavelength channel is not independently controlled. As a different approach, multiple optical modes selected from the frequency comb of a femtosecond laser were amplified through injection locking to slave DFB lasers to produce narrow linewidth as well as high wavelength stability [12]. However, this injection-locking method suffers a narrow locking range of each channel because the optical mode extracted directly from the frequency comb has a tiny power which usually reaches just few hundreds of nW.

In this investigation, the previously attempted two distinct approaches are combined into an all-fiber-based scheme in which multiple wavelengths are generated in parallel from a single compound ring-cavity oscillator. At the same time, all the generated wavelengths are stabilized real time by means of phase locking to the frequency comb of a fiber femtosecond laser. As each channel is pumped by a separate laser diode, the line power of the final cw laser output is in proportion to the number of channels without significant power variation between channels. The proposed method is aimed to demonstrate unprecedented performance in terms of not only the channel linewidth but also the wavelength stability and absolute uncertainty over a 5 THz spectral bandwidth covering the whole C- and L-bands in the ITU-T grid [13].

2. Multi-channel cw lasers

Figure 1 illustrates the optical hardware system configured in this investigation using all fiber components. The designed system is basically a ring-cavity oscillator operated with reference to the frequency comb of a mode-locked fiber femtosecond laser. The oscillator’s ring cavity is constructed with multiple Er-doped fibers, arrayed waveguide gratings (AWGs) and a...
single-mode fiber. The Er-doped fibers are aligned in parallel between a pair of AWGs adopted for wavelength division and multiplexing. Each Er-doped fiber works as the gain medium for a single wavelength channel being supported by an individual pump laser diode. A fiber Fabry-Perot (FFP) cavity is inserted on the single-mode fiber to create transmission windows that permits only a single wavelength to pass through each of the AWGs channels. The generated wavelengths are independently stabilized within the oscillator loop with reference to the frequency comb.


Figure 2 presents the detail of how the proposed compound oscillator system works to produce cw lasers of multiple wavelengths. First, broad emission is obtained from the Er-doped gain fibers over a wavelength range from 1450 to 1650 nm. Second, the FFP cavity provides transmission windows repeated at every ~50 GHz. The finesse of the FFP cavity is ~200 so that each window has a 250 MHz width of 3 dB attenuation. The windows spacing determined by the free spectral range (FSR) of the FFP cavity is adjusted to precisely match the channel spacing allocated by the AWGs by varying the FFP cavity length. Third, the fiber oscillator has a 3.2 m cavity length, which itself functions as a fine spectral filter offering a narrow linewidth of tens of kHz with a 62.5 MHz FSR. In consequence, in every AWGs channel of 100 GHz spacing, only a single wavelength peak survives all the filtering processes of the compound fiber oscillator.

The output wavelengths from the oscillator are subject to temporal drift and also mode hopping being caused by environmental change [14]. The frequency comb to be used as the reference in suppressing the wavelength drift and hopping is created from an Er-doped fiber femtosecond laser which emits 100 fs pulses at a 100 MHz repetition rate with an average power of ~20 mW. In the first place, the frequency comb is stabilized by phase-locking the pulse repetition rate \( f_r \) as well as carrier-envelope-offset frequency \( f_0 \) to the Rb atomic clock [15–17]. More specifically, \( f_r \) is detected using a photo-detector and phase-locked to a 100 MHz RF signal provided from the Rb clock, while \( f_0 \) is monitored using a \( f-2f \) interferometer and phase-locked to a 20 MHz signal of the same Rb clock. Once the frequency comb has been stabilized, the output frequency \( f_{CW} \) of each wavelength channel is observed with reference to the frequency comb in the form of \( f_{CW} = mf_r + f_0 + f_b \) where \( m \) is an integer and \( f_b \) is the beat frequency. The output frequency \( f_{CW} \) is then coarsely positioned to the target AWGs channel by adjusting the input current of the 980 nm pump laser diode (LD) connected...
to each gain fiber (EDF) while monitoring the output wavelength using a wavelength meter. Finally, $f_{\text{CW}}$ is precisely stabilized by phase-locking the RF beat note $f_b$ to a 40 MHz signal of the same Rb clock by controlling the injection current to the pump LD.

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3. Performance evaluation

Figure 3(a) shows three sample channels generated at 1530.26 nm, 1531.07 nm and 1550.06 nm in terms of vacuum wavelengths. The spectra were measured using an optical spectrum analyzer (OSA; Anritsu, MS9710A). The wavelength values were precisely determined from their frequencies identified in the form of $f_{\text{CW}} = mf_r + f_o + f_b$; the RF parameters of $f_r, f_o$ and $f_b$ were known as being phase-locked to the Rb clock. In order to decide the integer value of $m$ without ambiguity, a separate wavelength meter (WS-U, HighFinesse GmbH) was used to measure $f_{\text{CW}}$ with a 30 MHz resolution which is less than the half of the pulse repetition rate $f_r$ (50 MHz). The spectral purity of each wavelength was verified, as shown in Fig. 3(b), while the pump power to the Er-doped gain fiber was varied from 150 to 550 mW. The test result showed no conceivable side modes in the measured spectra, confirming that only a single wavelength was generated from each channel as intended. The signal-to-noise ratio (SNR) of each wavelength was found larger than 64 dB, which sufficiently exceeds the threshold level of 40 dB required for coherent DWDM light sources. The output power measured for a 550
mA input current to the pump LD was 4.88 mW. The linewidth was measured less than the resolution bandwidth (RBW) of the used OSA, which was 9 GHz.

![Graph](image)

Fig. 3. Experimental verification. (a) Three sample wavelength channels. (b) Optical spectra of a single channel with variation of the pump power.

In order to quantify the linewidth in more detail, the beat signal between a wavelength channel and the frequency comb was observed using a RF spectrum analyzer (Advantest, R3267). The result is presented in Fig. 4(a). The RF beat spectrum showed the mode spacing of the frequency comb given by the pulse repetition rate ($f_p$) at 100 MHz with its second harmonic (2$f_p$) at 200 MHz. The other four peaks were the beat frequencies produced from neighboring comb modes. The observed peaks yielded a signal-to-noise ratio of ~36 dB without noticeable side modes; even though there was a large power difference of order of $10^4$~$10^5$ between the wavelengths channel output and the comb modes in beating. One of the beat frequencies was extracted and used as the error signal in phase-locking the output frequency of the wavelength channel to the Rb clock. The error signal was loop-filtered at 40 MHz and fed back to the input current to the pump LD. The change of the LD input current induces power-dependent change of the refractive index within the fiber cavity, which consequently permits controlling the absolute position of the output wavelength [18,19]. The sensitivity of the output frequency to the LD input current was ~400 kHz/mA. This method of wavelength control was found robust to environmental disturbance without movable elements involved the phase-locking process. Figure 4(b) presents the RF spectrum of the beat signal phase-locked to 40 MHz, from which the linewidth was precisely measured to be 24 kHz (FWHM). It is worthwhile to note that the measured linewidth is about three orders of magnitude narrower than those of conventional DFB lasers widely used for DWDM communications.
Figure 4. Generation Linewidth measurement. (a) RF spectrum of beat frequencies between a wavelength channel and the frequency comb. (b) Linewidth profile of the beat frequency (magnified view).

Figure 5 shows test results of the wavelength stability measured after stabilization to the frequency comb. Without stabilization, generated wavelengths suffered temporal drift and mode hopping due to temperature-induced cavity length variation. Especially, mode hopping to adjacent wavelength modes of 62.5 MHz apart occurred tens of times per 1°C temperature drift over an hour. With stabilization to the frequency comb, the effect of cavity length variation was well suppressed by control of the LD input current as demonstrated in Fig. 5(a); the beat frequency was well locked to 40 MHz with a standard deviation of 0.0147 Hz over 10 hours. The absolute positions of generated multiple wavelengths were verified using a wavelength meter (WS-U, HighFinesse) of 30 MHz resolution. The absolute uncertainty was evaluated using the relation of $\left(\frac{u(f_{CW})}{f_{CW}}\right)^2 = \left(\frac{u(f_r)}{f_r}\right)^2 + \left(\frac{u(f_o)}{f_{CW}}\right)^2 + \left(\frac{u(f_b)}{f_{CW}}\right)^2$ as presented in Fig. 5(b). In terms of the Allan deviation, the overall uncertainty was measured to be $2.24 \times 10^{-12}$ at an averaging time of 10 s using a frequency counter referenced to the Rb atomic clock.
4. Conclusions

In response to the demand on increasing the transmission capacity of DWDM optical communications, we have proposed a noble all-fiber-based scheme of continuous-wave Er-doped fiber laser to generate multiple wavelengths simultaneously with reference to the frequency comb of a mode-locked femtosecond laser. Each wavelength channel constructed in the form of ring-cavity fiber oscillator allowed the linewidth to be narrowed to ~24 kHz. Besides, phase-locking of the output wavelength to a designated optical mode of the frequency comb permits attaining an absolute uncertainty of $2.24 \times 10^{-12}$ (10 s averaging) over a broad spectral bandwidth of 5 THz. This outstanding performance of multi-wavelength generation would benefit high-speed DWDM communications by reducing the channel spacing below GHz or even MHz, and also by allowing for coherent data transfer and detection.

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