Generation of optical frequencies out of the femtosecond frequency comb for DWDM telecommunication

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We exploit the frequency comb of a fs laser as the frequency ruler to generate reference optical frequencies for multi-channel DWDM (dense wavelength-division multiplexing) telecommunication. Our fiber-based scheme of single-mode extraction enables on-demand generation of optical frequencies within the telecommunication band with an absolute frequency uncertainty of 9.1×10^{-13}. The linewidth of extracted optical modes is less than 1 Hz, and the instability is measured 2.3×10^{-15} at 10 s averaging. This outstanding performance of optical frequency generation would lead to a drastic improvement of the spectral efficiency for the nextgeneration DWDM telecommunication..

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1. Introduction (Times New Roman 10pt)

The frequency comb of a femtosecond (fs) pulse laser is the mode-locked combination of a large number of quasimonochromatic optical modes evenly spaced over a wide spectral bandwidth. Stabilization control of the frequency comb to the radio-frequency (rf) atomic clock provides all the optical modes collectively with a high frequency precision of one part in 10^{15}. This unique feature of being an excellent frequency ruler allows the femtosecond laser comb to lead to outstanding applications in various fields such as time/frequency measurement, spectroscopy, and length/distance metrology.

DWDM-based optical telecommunication could also benefit from the femtosecond laser comb to enhance the transmission capacity. Reducing the channel spacing below the 50 GHz ITU standard grid would increase the number of frequency addresses with improved spectral efficiency. To date, the task improving the DWDM technology has been attempted with various frequency combs of different generation principles such as the etalon based wavelength locker, multiple integrated laser, super-continuum spectrum slicer, and external cavity resonator with integrated phase modulation. However, all these on-hand frequency combs are not comparable to the femtosecond laser comb in the performance of linewidth narrowness and long-term frequency stability. Notwithstanding the important advantage, the femtosecond laser comb is not directly useable for the DWDM application because its mode spacing is too dense, being typically in the range of 50 to 300 MHz. Another drawback is the nW-level optical power of each mode, which is too weak to be directly utilized as the channel signal. Here, we demonstrate a fiber-based method of extracting a single mode at a time on demand for telecommunication

2. Single-mode extraction out of the femtosecond frequency comb

An Er-doped fiber oscillator (C Fiber, Menlo Systems GmbH) is used, which produces pulses of ~100 fs duration at a 100 MHz repetition rate with an average power of ~20 mW. For stabilizing the resulting frequency comb, the pulse repetition rate f_r and the carrier-offset frequency f_{ceo} are locked to the Rb atomic clock of an rf time standard.Extraction of a single mode from the comb is made through a composite filtering scheme that combines a scanning Fabry-Perot filter (SFPF) etalon with a fiber Bragg grating (FBG). The used SFPF etalon (FFP-I, Micron Optics) provides a ~50 GHz free spectral range (FSR) with a finesse of 200, resulting in multiple transmission windows equally distributed over the entire spectral range of the comb (Fig. 1b). Each window offers a narrow bandwidth transmitting only three consecutive modes; a central mode of higher amplitude and two side modes of attenuated amplitude. Next, the fiber Bragg grating offers only a single transmission window of relatively broad bandwidth of ~100 GHz. The spectral location of the

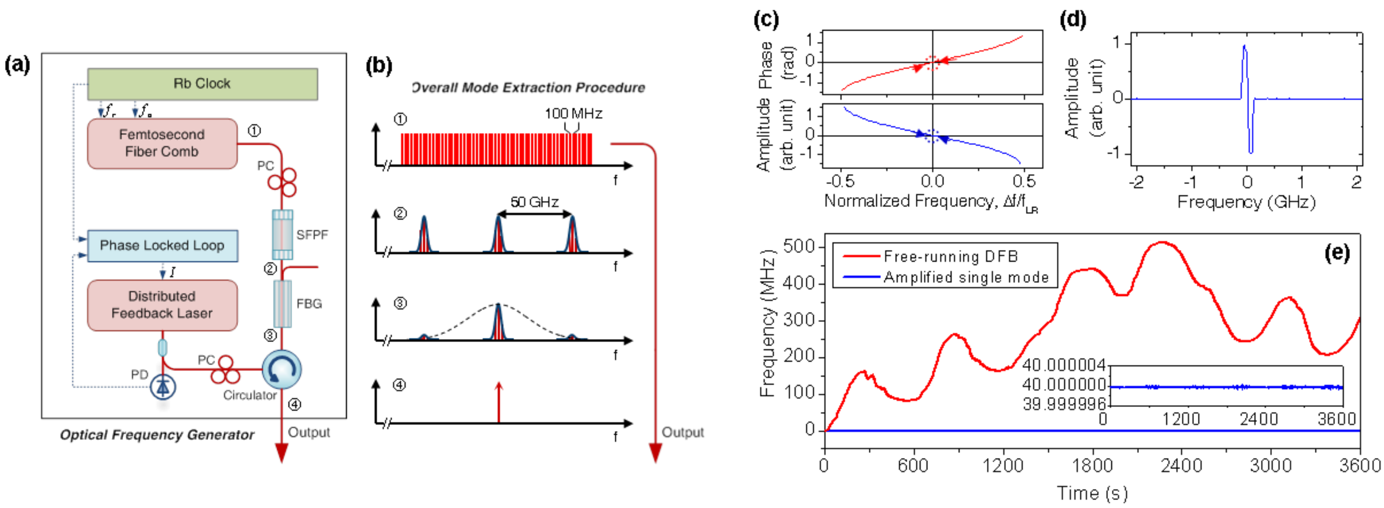

Fig. 1 Single mode extraction from the frequency comb of a fiber femtosecond pulse laser and long-term maintenance of injection locking (a) overall optical hardware configuration. (b) mode extraction procedure. (c) phase delay and subsequent control signal. (d) experimental control signal. (e) frequency fluctuation with and without injection locking

3. Single mode amplification through injection locking

The injection locking to a DFB laser diode enables the amplification of a weak seed optical signal by more than 50 dB with low background noise. The average power of a single mode just after being extracted from the femtosecond laser comb in this investigation is merely ~40 nW, which has to be boosted up to 20 mW. It is however important to note that the injection locking is successful only when the seed signal lies within the locking range of the DFB diode laser. The locking range f_L is narrowly confined to a small spectral slot of ~1 GHz with the free running frequency of the DFB laser as the center. The free running frequency varies with the cavity length, thereby the absolute position of locking range keeps drifting with the ambient temperature. Therefore, appropriate control action has to be taken to tune the locking range of the DFB laser to embrace the seed signal to be amplified. To maintain the injection locking, the locking range f_L of the DFB laser has to be adjusted all the time to the central mode extracted from the femtosecond laser comb. This task is achieved by varying the cavity length of the DFB laser so as to nullify the frequency offset Δf between the free-running emission of the DFB laser and the central mode. Fig. 1(e) shows an experimental result that demonstrates a low level of lock-in control instability of less than 1.3 Hz, whereas the free-running frequency of the DFB laser undergoes a large drift of more than 500 MHz within an hour.

4. Conclusions (Times New Roman 10pt)

Our fiber-based scheme of single-mode extraction from the frequency comb of a fs laser enables on-demand generation of optical frequencies for DWDM telecommunication with an absolute frequency uncertainty of 9.1×10−13. The linewidth of extracted optical modes turns out to be less than 1 Hz, and the instability is measured 2.3×10−15 at 10 s averaging with high immunity to environmental disturbances. This outstanding performance of optical frequency generation would enhance the spectral efficiency of the available optical band for the near-future telecommunication.

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