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Fiber Lasers for Frequency Standards in Optical Communications

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Abstract: Optical light with millihertz relative frequency stabilities and subfemtosecond timing jitter can be produced from stabilized cw or mode-locked fiber lasers. We will discuss the generation, fiber-optic distribution and some applications of these coherent sources.

OCIS codes: (120.3940) Metrology; (140.3510) Lasers, fiber

1. Introduction

Current telecommunication systems employing wavelength division multiplexing (WDM) are based on assigning a particular data stream to a particular optical frequency channel. For effective system operation, the center wavelength of the source laser as well as the various optical filters and other components in the link must be well characterized. The National Institute for Standards and Technology (NIST) has, for some years, provided calibrated reference gas absorption cells of acetylene, carbon monoxide, and hydrogen cyanide to provide absolute wavelength markers for the calibration of telecommunication measurement equipment.[1, 2] These absorption lines are calibrated with respect to an optical wavelength meter and are accurate to tens of megahertz, more than sufficient for current 10 Gbps data rates. However, to support requirements of even higher bandwidths, future systems will either expand into other wavelength regions or increase transmission efficiency within the current spectral region and will likely require the development of new, more accurate transfer standards. Therefore, we have recently worked on developing fiber-laser-based frequency combs,[3] which are based on the original Ti:sapphire frequency combs.[4, 5] The frequency comb is generated by stabilizing a mode-locked fiber laser to either an rf or optical reference source. The output forms a comb of optical frequency lines with herz-level accuracies across the entire transparent window of optical fiber;[6, 7] this comb can be used directly to measure an optical frequency, or indirectly to calibrate a less expensive transfer standard.

In addition to the absolute source wavelength, the source linewidth will likely be an important parameter in future applications in coherent optical communications, coherent LIDAR or fiber sensing. Therefore, we have also developed a cavity-stabilized cw laser source with hertz linewidths.[8] By phase-locking the fiber frequency comb to this single cw source, we can transfer its coherence to the fiber frequency comb. In the frequency domain, the output is then a comb of essentially “delta-function” reference optical lines each with a hertz linewidth. Such a highly coherent comb should have applications in measuring or generating highly coherent sources across the telecommunications band. In the time domain, the output is a pulse train with subfemtosecond timing jitter. Such a low-jitter pulse train should have applications of its own in precision ranging or linear optical sampling of high-bandwidth modulated signals.

We will discuss the development of highly coherent cw fiber-laser sources and mode-locked fiber-laser sources (i.e. fiber frequency combs) as well as the distribution of these highly coherent signals over fiber optic networks and some of their applications to frequency metrology in the telecommunications band.

2. Fiber-laser freqeuncy comb

Much of the original work on frequency combs used Ti:Sapphire lasers, [4, 5] but these combs cover mainly the visible region, and do not reach far enough into the near-infrared to cover the “transparent” window of optical fiber of 1.1 to 1.7 μm. In order to reach this spectral region, a number of researchers have been developing optical fiber laser-based frequency combs. (See Ref. [3] and references therein). To generate an optical frequency comb in the near infrared, pulses from a mode-locked fiber laser are launched into highly nonlinear optical fiber, which broadens the laser spectrum to a supercontinuum with a width of greater than 1000 nm. Since the laser is pulsed, this broad supercontinuum will actually be composed of discrete frequency lines – *a frequency comb* – spaced by the laser repetition rate. This optical frequency comb can be stabilized to provide discrete frequency or wavelength markers throughout the 1000 nm – 2000 nm region. Any unknown optical frequency can then be measured by simply comparing its frequency to that of the nearest tooth of the stabilized frequency comb. Fiber-laser-based frequency combs can be much more compact, robust, power-efficient, and lighter than bulk optic solid-state laser-based frequency combs, and commercial fiber-laser frequency combs are now available from several companies.[9 ,10] As shown in Figure 1, they can be phase-locked back to either an rf or optical reference source. In either case, the basic objective is transfer the coherence of the reference source to the entire comb. If the reference source is a 1 Hz linewidth cw laser, as discussed in the next section, then ideally each comb should have a 1 Hz linewidth. Various measurements have demonstrated that the comb can indeed transfer the coherence of such a 1 Hz laser across the entire frequency comb with sub-radian excess phase noise.[6, 7]

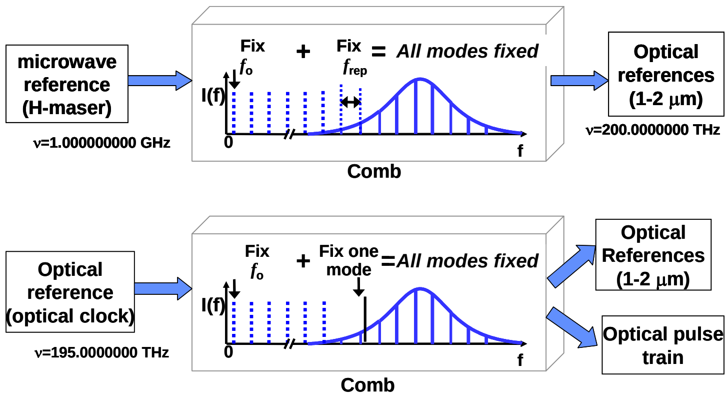

Fig.1. Schematic of the basic operation of a frequency comb. The comb can be referenced to either an rf or optical reference. In either case, its purpose is to faithfully translate the stability and coherence of the reference source across the optical spectrum.

3. Narrow linewidth CW Fiber laser

The linewidth of a cw fiber laser can be broadened by many effects, including intrinsic thermal noise in the fiber,[11, 12] external temperature fluctuations, external acoustic noise, and pump heating effects. The standard approach to quieting down such a cw laser is to phase-lock it to an external cavity. For a sufficiently tight phase lock to the cavity, the laser will take on the frequency properties of the cavity resonance. If the external cavity is made of very stable material and is sufficiently isolated from the environment, then the cavity resonance can be quite stable.

Following the extensive development of cavity-stabilized cw lasers,[13-16] we have constructed a stable cw laser at 1550 nm. Using the standard Pound-Drever-Hall technique, the laser is stabilized to an ultra-low expansion (ULE) cavity with a finesse of ~ 160,000.[17] The cavity is housed in a temperature-stabilized vacuum enclosure that sits on a vibration isolation table. The laser linewidth was measured by beating this laser with a frequency comb, which was stabilized to a very narrow 1126 nm laser, as discussed in Ref. [8]. The resulting linewidth is 1 Hz after removing an approximately few hertz/second drift as shown in Figure 2b.[8]

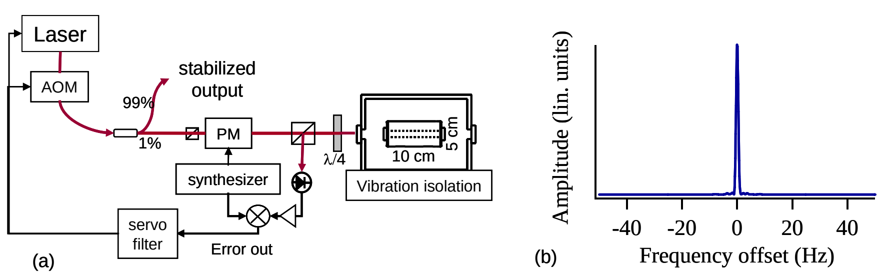

Figure 2: (a) Pound-Drever-Hall lock of the laser to the ULE optical cavity. (b) The resulting linewith of the stabilized laser, measured by recording 1.5 seconds of the beat note between this laser and a narrow-linewidth fiber frequency comb (described in the next section), and then Fourier transforming the signal. The linewith shown here is 1 Hz, as measured from the 1.5 seconds of data.

4. Applications to frequency standards

How one uses these highly coherent sources will depend on the application. One clear application of frequency combs is the calibration of secondary wavelength reference standards. Indeed combs have already played an important role in improved and ongoing measurements of molecular absorption lines or of laser systems locked to particular molecular absorption lines. [18-22] In the future a compact frequency comb could be referenced to a compact gas-filled fiber[23] to provide an absolute wavelength reference.

Some applications will require a highly coherent cw or comb source with sub-hertz linewidths and sub-radian optical phase noise. For such applications, a laser locked to a molecular line is insufficient since it will have at least a kilohertz instantaneous linewidth; instead, the direct output of either a narrow-linewidth cw laser or frequency comb source is needed. While these narrow-linewidth cw lasers and combs are currently expensive laboratory instruments, there is movement toward making them more robust, fieldable devices.[9, 10, 24] However, an alternative way to access the high stability and coherence from these sources is to transmit their output to remote sites across a fiber network. It is then relatively easy to phase-lock a laser at the remote site to the incoming coherent signal, as was done for the first experiments on coherent communications. We have conducted several experiments to explore the limitations of such coherent transport. In one experiment, an in-house coherent network was tested that involved the coherent transmission of a signal over both wavelength and distance.[7] In a second experiment, we have transmitted a coherent signal over a distance of 250 km of optical fiber by using techniques pioneered in the early 1990s.[25]

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