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Invited Paper

Coherent Fiber-Based Frequency Combs and CW Lasers at 1550 nm

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ABSTRACT

Coherent optical sources in the 1550 nm region of the spectrum have a number of applications in frequency metrology, stable frequency transfer, precision spectroscopy and remote sensing. A narrow-linewidth (~ 1 Hz) single-frequency source can be generated by phase-locking a cw fiber laser to a stable optical cavity. A comb of such narrow linewidth sources can be generated by phase-locking a mode-locked, femtosecond fiber laser to a single narrow cw source. We will discuss the current development of our narrow linewidth cw and pulsed sources at 1550 nm and some of the applications that can benefit from such coherent sources.

Keywords: narrow linewidth laser, frequency comb, frequency metrology

1. INTRODUCTION

The higher frequency of optical signals verses rf signals is advantageous in performing precision measurements. For this reason, the next generation of atomic clocks will operate in the optical rather than the rf regime. As another example, precision ranging and vibrometry measurements have long been undertaken in the optical regime because of the higher sensitivity to displacements. In order to exploit the high precision available from optical signals, highly coherent optical sources are needed. The 1550 nm spectral region is a particularly promising and interesting wavelength region because it overlaps the telecommunication band and is therefore compatible with existing telecommunication devices, optical fiber networks, and high power optical amplifiers. Coherent 1550 nm sources can support the wide distribution of coherent optical signals over either fiber optics or free space, and therefore can support applications ranging from laboratory-based optical frequency metrology to longer-range remote sensing. In this paper, we will discuss our efforts to develop coherent cw and pulsed optical sources in the 1550 nm spectral region, as well as some of the basic applications of such sources.

One well-established method for generating a coherent single-frequency or cw source is to phase-lock a cw laser to an optical cavity.[1] The frequency stability of the optical cavity is then transferred to that of the laser. Such cavity-stabilized sources have been developed for some time, in particular to support optical clocks.[2-7] We have constructed a similar cavity-stabilized system at 1550 nm. The laser has a linewidth of ~ 1 Hz and a frequency drift of several hertz per second. Even narrower linewidths and higher stabilities are certainly possible, but the current system has a coherence length ~ 3×10^8 meters, which is more than sufficient for most applications under consideration.

In the past few years, methods have been developed to stabilize pulsed lasers as well. Since the output of a pulsed laser is repetitive, it forms a frequency comb of individual spectral lines. Fortunately, there are only two degrees of freedom of this comb (*i.e.*, the spacing and translation); stabilization of these two degrees of freedom stabilizes the entire comb. Originally developed using solid-state mode-locked lasers in the visible and near infrared,[8-10] frequency combs have revolutionized optical frequency metrology. Frequency combs are now also being produced based on femtosecond fiber lasers and can cover the spectral region from 1 to 2 µm.[11-25] Provided the comb is tightly phase-locked to a one hertz-linewidth cw laser, the linewidth of each individual comb tooth can be similarly reduced to one hertz (with a residual linewidth that is much smaller).[24, 26] Note that for such phase coherent cw and comb sources, once the residual phase noise drops below ~ 1 radian, the residual linewidth is transform-limited, and linewidth is no longer a particularly relevant measure of the source coherence; a better measure is given by the phase noise spectrum in analogy with specifications for low-noise rf or microwave oscillators.

The organization of the paper is as follows. In Section 2, we will describe our current cavity-stabilized cw laser at 1550 nm. In Section 3, we will review our narrow-linewidth fiber laser frequency comb. In Section 4, we will outline some of the applications possible with these sources, and finally conclude in Section 5.

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2. 1 HZ LINEWIDTH CW LASER

The linewidth of a cw fiber laser can be broadened by many effects, including intrinsic thermal noise in the fiber,[27, 28] 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,[2-7] we have constructed a stable cw laser at 1550 nm. Figure 1 shows a picture of the ULE cavity and a measured transmission resonance. The finesse is ~ 160,000. The cavity is then housed in a temperature-stabilized vacuum enclosure that sits on a vibration isolation table. Recently, there has been significant effort to reduce the vibration sensitity by novel cavity designs,[4] and such designs will obviate the need for a vibration isolation table. A Pound-Drever-Hall technique is used to phase-lock the cw fiber laser to the cavity, as shown in Figure 2.[1]

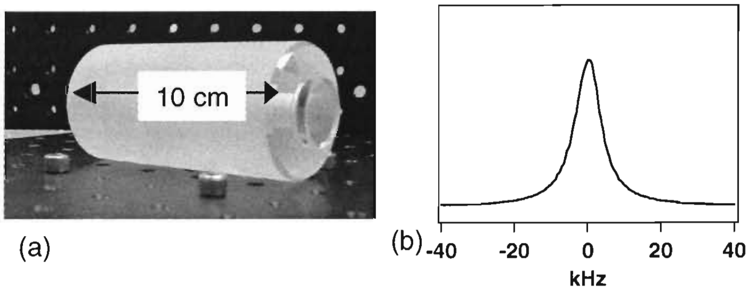

Figure 1: (a) Picture of the ULE cavity deigned for 1535 nm operation. The spacer is 10 cm long with a hole bored through the center. The mirrors are ULE substrates coated for high reflectivity at 1535 nm. (b) The resulting transmission resonance through the optical cavity, measured by sweeping a laser locked to a frequency comb across the cavity. The full width at half maximum (FWHM) is 9 kHz, compared to the free spectral range of 1.5 GHz.

The performance of the laser is often measured by beating two such cavity-stabilized lasers against each other. Here, we have thus far constructed only a single system. Therefore, we beat this laser with the frequency comb, which was stabilized to a very narrow 1126 nm laser, as discussed in Ref. [29]. The resulting linewidth is 1 Hz after removing an approximately few Hz/second drift as shown in Figure 2b.[29]

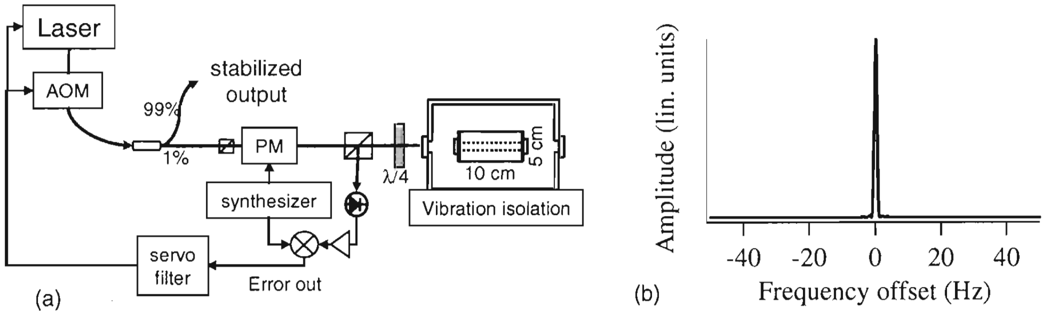

Figure 2: (a) Pound-Drever-Hall lock of the laser to the ULE optical cavity. An external AOM is used since the feedback bandwidth to the laser piezo-electric transducer is not quite sufficient for a tight phase lock. (b) The resulting linewith of the stabilized laser, measured by recording 1.5 seconds 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

3. NARROW LINEWIDTH FREQUENCY COMB

The basic concept of the frequency comb was first demonstrated with solid-state Ti:sapphire lasers,[8-10] but the same basic principles apply to the femtosecond fiber-laser based comb.[11-25] Figure 3 shows the standard picture of the frequency comb; a pulse train in time produces a frequency comb in space. In this picture noise is ignored, so that the frequency comb lines are delta functions. In reality there will be noise on the system. In the time-domain picture, this noise will be manifested as "fuzz" on the carrier wave and as jitter on the pulse envelope. In the frequency-domain picture, this noise will be manifested as a blurring of the individual comb teeth. Therefore, to remove this noise and stabilize the frequency comb, it is phase-locked to a reference in either the microwave or the optical domain.

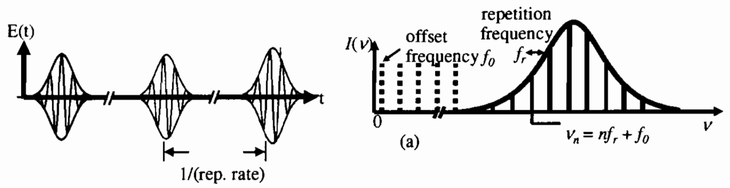

Figure 3: Standard time-domain and frequency-domain picture of the comb. In practice, there will be noise on the comb. If that noise level is large, the comb teeth can be quite broad. If that noise level is low, the comb teeth will be narrow and rest upon a phase noise floor.

A schematic of the fiber laser frequency comb is shown in Figure 4 and comprises a mode-locked femtosecond fiber laser,[30] an erbium-doped fiber amplifier to increase the pulse energy, and a highly nonlinear fiber to broaden the spectrum to cover an octave[31] so that the comb offset frequency can be detected using the standard f-to-2f interferometer.[9, 32, 33] When locked to an rf reference, the comb repetition rate is phase-locked by feeding back to the cavity length, and the comb offset frequency is phase-locked by feeding back to the pump power. However, to realize very narrow comb lines, an rf reference does not have suitable phase coherence. (In other words, by the time the phase noise of the rf source is multiplied up to the optical region it leads to very broad comb lines.) Therefore, instead, a single comb tooth is locked to a narrow optical source, for example, such as the one described in the previous section. The offset frequency can then be locked to an rf reference.

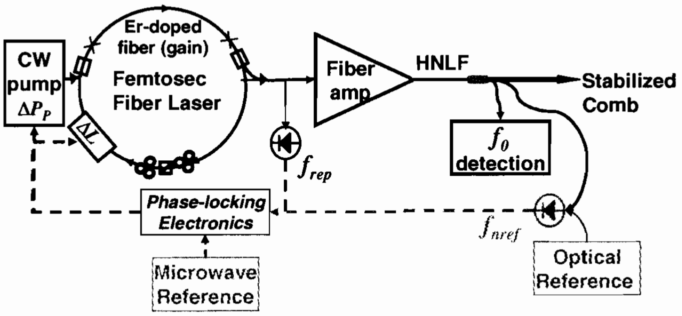

Figure 4: Basic schematic of a fiber laser frequency comb. The femtosecond fiber laser output is amplified and spectrally broadened in highly nonlinear fiber (HNLF). The offset frequency is phase-locked to a microwave reference. The remaining degree of freedom of the comb can be stabilized through (1) phase-locking the repetition rate to a microwave reference or (2) phase-locking one tooth of the comb to an optical reference (shown in gray). Solid lines represent fiber optic paths and dashed lines represent electronic signals.[34]

The fundamental purpose of the frequency comb is to transfer the properties of the reference (either the microwave or optical reference) to each comb tooth. On long time scales, this effect is quantified in terms of the relative frequency stability of the comb. On shorter time scales, this effect is quantified in terms of the relative phase noise between the reference source and the comb. Clearly, if the comb had no noise of its own, then it should be relatively straightforward to phase-lock it to a reference of very low noise. Unfortunately, the fiber comb does suffer from a variety of noise sources that need to be effectively cancelled through feedback.[34] Regardless of the source of the noise, it can be cancelled provided the feedback is sufficiently strong, in other words, provided the feedback has sufficient bandwidth. The bandwidth of the feedback to the cavity length is limited by the transducer used to effect changes in cavity length. A piezo-electric transducer (PZT) can reach 30 kHz of bandwidth. The bandwidth of feedback to the pump power can be even larger, provided the rolloff in the laser response is appropriately compensated.[21, 22] Using tight phase locking, it has recently been possible to narrow the comb lines so that they suffer from less than a radian of relative phase noise. At these low phase noise levels, the comb lines are indeed delta-functions, with a transform-limited linewidth that rests upon a larger phase noise pedestal. Our current frequency comb is described in much greater detail in Ref. [34]. Figure 5 shows the locked and unlocked offset frequency signal. Figure 6 shows the locked and unlocked optical beat signal between a comb tooth at 1550 nm and the cavity-stabilized laser discussed in the previous section. These figures show the in-loop phase-locked signals and therefore demonstrate that the phase-locking bandwidth is sufficient to phase-lock the relevant comb teeth tightly. The underlying assumption of the frequency comb is that, by doing such a phase lock, all the remaining teeth of the comb are similarly stabilized. A number of measurements verify this is true to a high degree, as reviewed in the next section

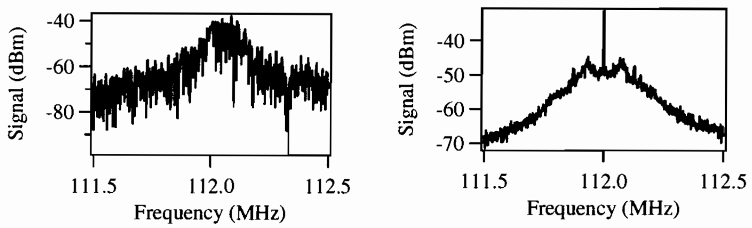

Figure 5: Unlocked and locked offset frequency signal. The coherent peak in the locked signal occurs when the integrated phase noise drops below 1 radian.

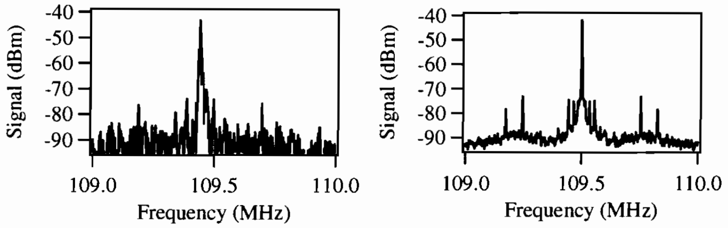

Figure 6: Unlocked and locked beat note between the cavity-stabilized laser and the comb tooth at 1550 nm.

4. TEST OF LASER/COMB PHASE NOISE

Two different types of measurements are used to quantify the fidelity of the frequency comb, in other words, how faithfully it reproduces the reference source. In one measurement, the relative frequency stability of the comb is measured and quantified in terms of the Allan deviation. In another measurement, the relative phase noise of the comb teeth is measured and quantified in terms of a phase noise spectral density. In some sense, these are both measurements of the phase coherence, but the measurement of frequency stability probes the phase coherence at very long times (seconds to days) while the phase noise spectral density probes the noise at shorter times (seconds down to microseconds).

As part of a large collaboration, we have conducted several tests of the comb fidelity. In a first experiment in collaboration with IMRA America, OFS and Stanford, we phase-locked two fiber laser frequency combs to a common reference. We then heterodyned together different spectral components of the comb. The result was a very narrow beat signal with ~ 1 radian integrated phase noise across the entire comb spectrum. In a second experiment at NIST, a large coherent fiber-optic network was assembled that combined the fiber-laser frequency comb, a Ti:sapphire frequency comb, several cavity-stabilized cw lasers, and several Doppler-cancelled fiber-optic links.[26] The two frequency combs provided nodes of the network where the optical frequency of the source could be translated from 1.1 μm to 760 nm (in the case of the Ti:Sapphire comb) or from 1.1 μm to 1.535 μm (in the case of the fiber frequency comb). We found that the phase noise of light propagated around the fiber network and across the spectrum could be predicted by the various phase-locks in the network down to about 10 Hz Fourier frequency. Below 10 Hz, length noise on short "out of loop" paths within the system causes excess noise on the beat signal. In these tests, the relative frequency stability of the comb was also tested. The Allan deviation, or fractional frequency instability, was ~6×10^{-17} at one second and drops to ~2×10^{-18} at 1000 seconds. This stability is more than adequate for transferring stable optical signals, such as might be encountered in optical clocks and frequency transfer, coherent communications, and other applications. Furthermore, the frequency stability appears not to be limited by any properties of the comb; rather, it is limited by short "out-of-loop" sections of optical fiber or air path that contribute small Doppler shifts of the propagating light due to temperature fluctuations.

5. APPLICATIONS OF A LOW-NOISE COHERENT SOURCE AT 1550 NM

Although the original impetus for developing frequency combs was optical frequency metrology, the number of applications of frequency combs is growing. We discuss some of these applications below, in particular those that benefit from both a low-phase-noise cw and comb source in the 1550 nm region.

5.1 Frequency metrology

Optical clocks require the measurement of optical frequencies to a very high relative stability, and this application drove the original development of frequency combs.[8] A unique feature of the frequency comb is that it provides a phase-coherent link between microwave frequencies and optical frequencies. Essentially it allows one to count the optical frequencies. In order to emphasize this point, Fig 7 shows different methods for measuring the frequency of a signal in the 1550 nm region. There are many orders of magnitude over which only the frequency comb can provide a reliable measurement.

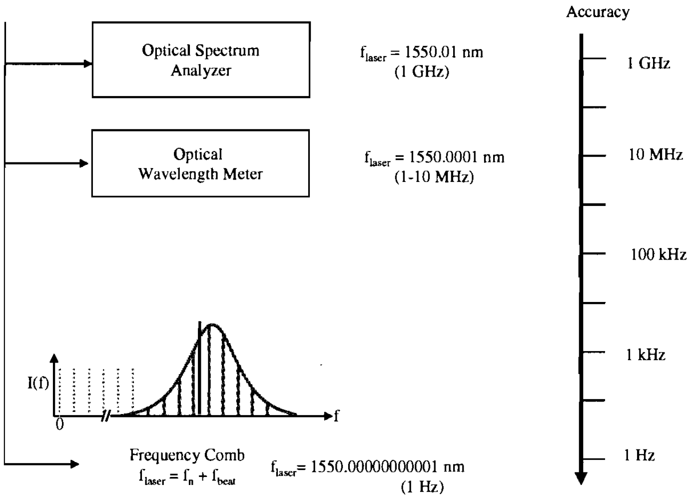

Fig 7. Comparison between available methods for determining the frequency of a source in the 1550 nm region. For a measurement with the frequency comb, the frequency of the laser is given by the sum of the beat frequency with the nearest comb tooth and the frequency of the comb tooth.

5.2 Frequency transfer

One of the main reasons to work near 1550 nm is the availability of fiber optic networks of very low loss. As mentioned in an earlier section, a coherent fiber-optic network was set up at NIST to transfer stabilized light around the building and to test the stability of the comb. The main purpose of such a network, however, is not to test the comb but rather to transmit the very stable, low-jitter signals generated from state-of-the-art optical clocks to remote locations. To this end there has been significant effort recently at transferring very stable frequencies over optical fiber networks.[26, 35-37]

There are a number of approaches to this problem. In once case, the desired frequency is transported in the microwave domain by amplitude modulation of a 1550 nm signal that is then sent down the fiber.[36, 37] However, higher stabilities and lower timing jitter can be expected if a fully stabilized optical source is used. Either the comb pulses themselves can be transmitted, or portions of the comb can be transmitted at, say, two ends of the comb.[38] The approach we have taken involves simply sending the cavity-stabilized cw laser light itself and stabilizing the link using a well established Doppler cancellation technique.[39-41] At the remote end, the optical carrier can be converted to the desired optical or microwave frequency using optical frequency combs. Recently, Grosche et al. have demonstrated transfer over 211 km of total optical fiber length that included 86 km of deployed fiber using this method.[35] In earlier pioneering work, Ye et al. transferred an optical carrier over 7 km of installed fiber.[41] We have recently demonstrated transfer over a 251 km link that includes 76 km of lossy installed optical fiber, 175 km of fiber spools and four in-line erbium-doped fiber amplifiers (EDFAs) to periodically boost the signal.[42] Very high residual instabilities are possible even at these long distances.

5.3 Spectroscopy

A second application of stabilized sources is laser spectroscopy, where the comb's broad coverage guarantees overlap with many interesting spectral features, and the accurately defined comb line locations give absolute information on the location of these features. One way to use frequency combs for spectroscopy is to follow a technique originally developed in the microwave regime and later used in the terahertz regime.[43-45] The basic idea is to transfer the comb spectrum into the radiofrequency (RF) domain. This is accomplished by combining the output of two optical combs operating at slightly different repetition rates but otherwise phase-locked together into a single signal. In the RF domain, this signal appears as a comb of RF lines separated by the difference in repetition frequency of the two combs. Each tooth in this RF comb represents a beat signal between two particular comb teeth at a very well known optical frequency. This approach does require two stabilized frequency combs of very low relative phase noise, but the detection is quite simple and the approach is entirely compatible with existing spectrometers using a single photodetector.

5.4 Remote sensing (LIDAR)

The stabilized frequency comb has extremely low timing jitter, and therefore has immediate applications to precision ranging. At AIST, distance has been measured very precisely using the rf comb output of the frequency comb.[46] The optical output of the comb can also be used directly. It has the advantage of providing a very broadband coherent source, which can be ideal for coherent range/Doppler Light Detection and Ranging (LIDAR). We have conducted some initial experiments on a laboratory-based range-Doppler LIDAR.[47] A drawback of the approach taken in this initial work is that it had only a limited range of regard. To solve this problem, one can use two phase-locked frequency combs; one comb acts as a transmitter while the other acts as a local oscillator (LO). The LO can be tuned to overlap the return signal, allowing for a much wider range of regard. The high phase coherence of the comb should also assist in synthetic aperture LIDAR experiments and allow the system to avoid the otherwise extensive processing required to generate the full synthetic aperture.[48]

6. CONCLUSION

We have summarized our current low phase noise cw and pulsed laser sources that operate in the 1550 nm region. Currently, the phase noise is on the order of 1 radian and the linewidths on the order of 1 Hz. Further improvements in the phase noise of these sources are possible. However, even at their current level of performance, these sources should enable many applications. The frequency comb stability is more than adequate to support current state-of-the art optical clocks, and the linewidth of the current cavity-stabilized laser is more than adequate to support long range experiments over either fiber or free-space. One of the main future areas of research will likely be to make these sources even more compact and robust, while maintaining their current level of performance, so that they can move out of the laboratory and into the field.

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