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A New Frequency Distribution Architecture for Wavelength Division Systems

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Abstract

Frequency division multiple access (FDMA) is a prime channel access method for wide-band fiber-optic communication networks. It has the potential to support thousands of channels. One of the key issues in such a system is the distribution and identification of transmission frequencies. In the first part of the paper we review techniques for frequency stabilization that have been proposed. In the second part we propose a frequency distribution architecture that appears to have many desirable characteristics and we report some experiments that indicate its feasibility.

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1 Introduction

Frequency division multiple access appears to be one of the most feasible ways to exploit the huge bandwidth of single mode optical fiber. In that method a separate optical frequency band is allocated to every "conversation", either on a preallocated or on a dynamic basis. The low attenuation windows of conventional single mode fibers have bandwidths measured in tens of nanometers, i.e. in terahertz. Current technology, using either coherent receivers or optical filters, is capable of spacing the channels by as little as about a gigahertz. Thus the potential exists to support thousands of simultaneous conversations. A key problem in that scenario is that of frequency stabilization as the oscillation frequency of a laser diode is extremely sensitive to the environment, varying by about 12GHz per °K and 1GHz per mA of bias current for DFB lasers at 1.5 μm. The long term frequency stability of a laser diode (for a fixed environment) is not yet well understood [35].

In the first part of this paper we review various methods that have been proposed to stabilize laser frequencies. In the second part we note that the proposed methods are not immediately applicable to large user populations, we outline a new frequency stabilization architecture and we report on some feasibility experiments.

2 Review: frequency stabilization

Physicists have dealt with the issue of frequency measurements for a long time and communications engineers have reused many of their techniques. We limit our review to optical communication studies, mainly in the bands around 1.3 μm and 1.5 μm, although we also touch on applications at 0.8 μm. Due to space limitation we do not comment on the accuracy of the various methods, great accuracy is not critical for FDMA systems. Several excellent review papers, e.g. [36] and [53] should be consulted to obtain a more complete picture than that presented here.

We classify the frequency stabilization methods in four categories. In the first category one uses natural sources of oscillations, such as atomic and molecular resonances. This permits absolute frequency measurements. Methods in the second category utilize the characteristics of man-made devices, such as optical filters and resonators. These first two categories are mostly appropriate for stabilizing a single laser. The third category monitors many sources at a central site, while the fourth distributes frequency references from a central site. Thus the last two categories aim at frequency synchronizing multiple sources relative to each other.

2.1 Locking to atomic and molecular resonances

Many experiments have been performed locking lasers to atomic or molecular absorption lines. One typically passes light from a laser through a cell containing a gas such as acetylene (C_2H_2) [45], [46] or ammonia (NH_3) [34], [56], [57], or even water [34] and one measures the received power. To identify the peak of the absorption one usually dithers the frequency of the laser and one uses a lock-in amplifier (i.e. a correlator). However White et al. [55] (at 632 nm) and more recently [52] (at 780 nm) and [9] (at 1.5 μm) have dithered the frequency of the absorption line with an a.c. magnetic field, using the Zeeman effect. This technique has advantages in an FDMA communication environment.

Instead of relying on absorption line, one can also use the optogalvanic effect, i.e. the impedance change in a gas discharge tube when light at an appropriate transition frequency is transmitted through the cell. This has been reported many times, e.g. [21], [5], [6], [8], [31]. A survey of atomic transitions suitable for the optogalvanic effect in the 1.3 - 1.5 μm region appears in [28].

The locking of many lasers to neighboring Rb resonances (around 780 nm) has also been demonstrated [54], [49], but the number of available lines is only 4 or 6. Similar results have also been obtained recently [39] at 1.5 μm, using C_2H_2. Dozens of lines appear to be available. In either case the frequency spacing is determined by nature, which may not suit the transmission requirements.

2.2 Locking to optical filters and cavities

This class of techniques was first introduced by Bykovskii [3] in 1970 with the aim of reducing the linewidth of diode lasers, rather than of measuring frequency. Lasers can be locked to the side of the transmissivity curves of temperature compensated narrowband interference filters [21] and Fabry-Perot filters [10], [37]. There is no need to dither the laser frequency, the measurement can be obtained by comparing the optical powers at the input and output of the filter.

Locking to a resonance peak of a Fabry-Perot filter has also been accomplished [42], [4]. [42] used a high laser dither frequency (400 MHz) and relied on the beat between harmonics to generate the feedback signal, a technique initially developed for frequency modulation spectroscopy. Glance [14] on the other hand has used the "natural" dithering caused by Frequency Shift Keying (FSK), which is very attractive for communications systems.

Fiber-optic ring resonators have a frequency response similar to that of Fabry-Perot filters. They have also been used to stabilize an external-cavity laser diode [47], and DFB lasers [48]. In this last experiment the ring was integrated on a silica base.

2.3 Monitoring at a central site

Many proposed optical FDMA systems have all stations broadcast their signals. It is thus feasible to monitor all frequencies at a central site. Bachus [1] used the Heterodyne Spectroscopy method in which a laser is frequency scanned and made to beat with the signals received from the stations. The times at which beat tones are detected can be translated into frequency offsets. This method is also reported in [11] and [2]. It has the capability to control sources that are not equally separated, but it relies on knowing precisely at all times the frequency of the scanning laser. Another approach [40] avoids this problem by dividing the output of the scanning laser in two parts. One part is used to generate beat signals as before, the other part is passed through a Fabry-Perot filter, and generates a "Reference Pulse" each time it crosses a resonance. Effectively the Fabry-Perot filter is used to calibrate the frequency of the scanning laser. As proposed, feedback is used to align the frequencies of the lasers with the resonance peaks, which forces the frequencies to be equally spaced. One could combine the two methods and use timing information together with reference pulses to have both high accuracy and flexibility. Note that both methods rely on the availability of a continuously tunable laser source, which would limit the bandwidth that can be used.

Similar to the Heterodyne Spectroscopy method, a scanning Fabry-Perot cavity can be used to measure laser frequencies. This has been introduced in [33] and [50]. Analog implementations have also been described [12], [13]. Maeda [30] also used this scheme in a system demonstration with 16 channels. In addition she achieved absolute frequency stabilization by locking the Fabry-Perot to an absorption line of gaseous ammonia.

As in the Heterodyne Spectroscopy method, the scanning Fabry-Perot method allows the channels to be spaced arbitrarily, but it is critical that the peak frequency be precisely known at all times. The method may be limited as the finesse needs to be much greater than the number of stations. This problem may be solved by using a cascade of Fabry-Perot filters.

Instead of using a scanning Fabry-Perot Glance [14] uses a fixed interferometer followed by a single photodetector to lock many users, each to a different peak. That method relies on FSK modulation of the various lasers with uncorrelated data streams, and it requires that these streams be known at the central site. This would only be possible for co-located sources. The Fabry-Perot has also been locked to an absolute reference, using an auxilliary laser and the optogalvanic effect [7]. A ring resonator has also been used [51] in almost the same setup, except that frequency dithering of the laser diodes and synchrounous detection was used to provide feedback. Again this requires co-located sources.

2.4 Broadcasting from a central location

Another approach for the stabilization of many laser sources is to broadcast a comb of laser frequencies. They are usually produced either by phase modulation [20],[17], [22] or direct frequency modulation [30] or amplitude modulation (possibly with mode locking) [24], [23], [25], [18] of a carrier. The slave lasers can be controlled either directly by injection locking [16], [23], or by heterodyne detection and frequency [20], [30], [26] or even phase [22] locked loops. The number of sidebands that can be produced is counted at most in dozens. Instead of using carrier modulation, [19] has suggested producing a pulsed frequency comb by periodically feeding a short pulse at one frequency through a loop containing an amplifier (so as to have about unit loop gain) and a frequency shifter. This arrangement periodically produces a sequence of short pulses equally separated in frequency. A key advantage of the method is that any frequency can be isolated at the receiver by gating the signal at a prescribed time with respect to the beginning of the period, thus overcoming the need to mark individual teeth of the comb. In the initial experiment 35 tones were produced.

Alternatively some of the methods considered previously can also use a frequency broadcast from a central site. For example in the Reference Pulse method [41] the direct output of a single scanning laser and the output of the resonator could be distributed to remote locations using separate fibers. There local lasers are made to beat with the master laser signal and the time differences between the apparitions of local beat tones and the apparitions of pulses from the output of the central resonator are used to provide feedback.

Glance [15] has also demonstrated a system using one Fabry-Perot device at each node of the network. They are adjusted so that a reference tone distributed from a central location coincides with a resonance peak. However the remote nodes had to know the signal used to dither the reference tone.

3 Comments on the proposed methods and outline of a new architecture

After considering the methods proposed in the last section, we conclude that absolute frequency stabilization techniques are probably too expensive to use at each site in a distributed environment. Natural transition frequencies do not always exist where they are needed, so that to use them each node would have to be provided with circuits that essentially amount to a wavemeter. However absolute frequency stabilization at well chosen frequencies is very feasible and it could be helpful to absolutely stabilize a common reference source. This feature is not required in FDMA systems but may become necessary to insure that devices operate at their design frequency, or when many independent FDMA networks are interconnected.

The frequency monitoring methods at a central site suffer from a number of problems. They have limited bandwidths, they are slow when the number of nodes is large, and they can hardly handle the startup problem, i.e. making sure that when a laser is first turned on its output is at the correct frequency.

Systems where a central node broadcast reference frequencies do not suffer from the startup problem but they normally require an extra fiber to carry the comb. The number of tones they can provide appears to be rather limited, although the initial results of the pulsed comb method seem to be promising.

The distributed Reference Tone method has a limited bandwidth due the presence of the scanning laser and it requires extra fibers for frequency distribution. Overall the method proposed by Glance, i.e. using one Fabry-Perot resonator in each node appears to be the most desirable.

Fiber based Fabry-Perot [43], [44] are becoming widespread [32] and possibly cheap. Being mechanical devices they have a slow reaction time, which is an advantage in this case. Fiber ring resonators are even simpler structures that might also be used, although they may exhibit an undesirable sensitivity to polarization.

The method proposed in [15] to align the various Fabry-Perot filters cannot easily handle thousands of nodes. The fact that all filters have a common resonance at the reference frequency does not insure that all their transmission peaks are aligned. For this to occur the optical length difference between the two devices must be much smaller than their nominal length divided by the number of channels. This leads to difficulties in manufacturing and requires stabilization of the environment.

To solve this tolerance problem we propose to use a wideband Light Emitting Diode (LED) as a frequency reference. More precisely at a central site light from an LED is passed though a master Fabry-Perot (Figure 1). The output from that cavity is broadcast, possibly on the same fiber as the data signals, to all remote locations. There it is passed through adjustable slave Fabry-Perots whose outputs are connected to power meters. When the length of a slave is adjusted, the measured power exhibits a series of sharp pulses (Figure 2). One sees from the figure that there is a sharp central peak that corresponds to the case where the slave has exactly the same optical length as the master. When that condition is realized all the transmission peaks of both devices are expected to coincide. That method has been used before to control the parallelism of Fabry-Perot mirrors [38]. The upper envelope of the pulses in Figure 2 can be shown [27] to follow a curve approximately given by $\arctan(BFd)/BFd$ where B is the ratio of the LED linewidth to the central frequency, F is the finesse of the cavities, and d is the optical length difference in units of wavelengths. Thus the secondary peaks will be distinctly smaller than the main peak for $BF > 1$, which is easily feasible. Note that the previous formula does not depend on the free spectral range.

The curve of figure 2 was experimentally measured at .8 μm, using bulk Fabry-Perot devices with a finesse of 45 and a free spectral range of 15 GHz. The LED bandwidth was about 50 nm.

We have also demonstrated locking the slave Fabry-Perot to the master, using the setup of Figure 3. The LED was unmodulated and the slave Fabry-Perot was dithered at about 160 Hz by about 200 MHz peak to peak. The output of the power detector was fed back through a lock-in amplifier. Lock was achieved with a power level of about 500 pW (-63 dBm) at the input of the slave Fabry-Perot. At that power level the rms feedback voltage corresponds to a frequency error of about 100 MHz, which is similar to the error caused by the 60 Hz noise ripple from the Fabry-Perot driver circuit. No study has yet been done to pinpoint the noise sources.

Note that in practice the LED should be modulated at 100 kHz or so and a narrowband filtering circuit should be used to estimate the power level at the photodetector. Doing so would both reduce the influence of the $1/f$ noise from the photodetector and allow operation in presence of data modulation. One may also want to continuously compare the levels of the LED signals before and after a slave Fabry-Perot, as their ratio would indicate if the devices are in lock on the main peak.

The presence of the LED signal should not significantly impair data transmission, as it is spread over an enormous bandwidth. The fact that the slave Fabry-Perot is dithered should make it easy to lock local lasers to it. However it may be difficult to lock a FSK modulated laser [42]. The master Fabry-Perot could be locked to a frequency standard to achieve absolute stabilization.

The free spectral range of the Fabry-Perot could be much smaller than the channel separation, thus permitting channel spacings at integer multiples of a small unit. However there is a lower limit to how small the free spectral range can be, e.g. due to effects such as polarization sensitivity and stability of the Fabry-Perot cavity

As in all Fabry-Perot locking schemes, the problem remains to distinguish between resonance peaks. This would probably be done by broadcasting "well known" signals at prespecified frequencies. These signals could be modulated and transmit system maintenance and control information. The local laser would be used as in the Reference Pulse method to identify the resonances.

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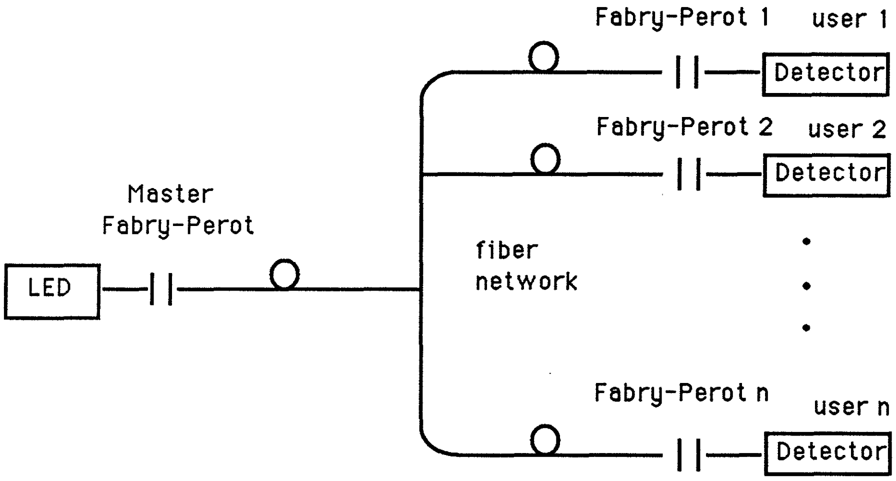

Figure 1. LED light passes through the master Fabry-Perot and is broadcasted to users.

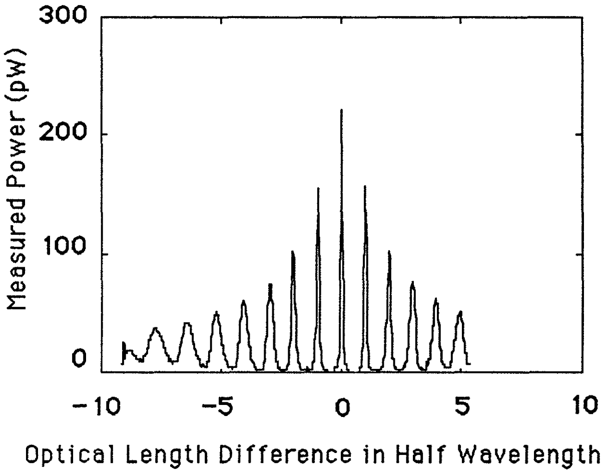

Figure 2. Measured power as a function of optical length difference.

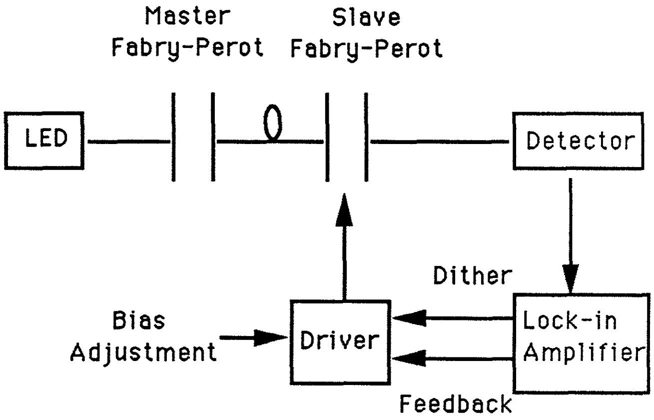

Figure 3. Experimental setup for locking a slave Fabry-Perot to a master Fabry-Perot.