Coherent Technology in Fiber Optic Systems

Virginia A. Ormiston, Frederic Ouan
Chairpersons/Editors

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COHERENT TECHNOLOGY IN FIBER OPTIC SYSTEMS

Volume 568

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Session 1—Systems Issues
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Session 2—Fiber Considerations
Frederic Quan, Corning Glass Works

COHERENT TECHNOLOGY IN FIBER OPTIC SYSTEMS

Volume 568

INTRODUCTION

Optical coherent technology is attracting interest because of the promise of longer repeaterless distances and greater information-carrying capacity for existing and planned fiber routes. Researchers, corporate and academic, are just beginning to zero in on coherence methods for surpassing the simple, long-distance optical systems deploying direct detection today, and for increasing even more the capability of the telephone distribution plant. This conference marks the advent of a very significant technology within the field of fiber optics.

To display the diversity and breadth of present research, the conference is divided into two sessions. In Session 1, Systems Issues, some interesting coherent technology system issues are discussed; they should be invaluable to the transmitter, receiver, and systems designers. The papers in Session 2, Fiber Considerations, focus primarily on the passive elements and fiber considerations that naturally follow.

In the first session, an overview of coherent detection technology is presented in the first paper by B. Basch, R. Kearns, G. Joyce, S. Stone, and W. Chen. The paper addresses the types of detection techniques available and lists the advantages of using coherent detection over direct detection methods. This paper should be read by those new to this technology and also used as a convenient reference for terms used frequently in discussions.

The second paper, by R. S. Vodhanel, gives some of the source considerations that will be needed to design coherent systems. More source information is also presented in the third paper, by M. Minemura, M. Shikada, I. Mito, and K. Kobayashi. Together, the two source papers should give insights to the technology available and the requirements that sources of future coherent systems should meet. L. G. Kazovsky examines receiver design in the fourth paper. Simple block diagrams of coherent receivers are given along with laser requirements within the receivers. And, in the fifth paper S. Ramesh, C. A. Goben, V. Aalo, and O. Ugweje evaluate the intersymbol interference that could be found in a coherent detector using a computer model.

The second session builds on the technology presented in the first session with a stress on the more practical considerations of a coherent system. In the first paper H. Kobrinsky illustrates a scenario where coherent systems are used to distribute telecommunication services to customers (i.e., as could be found in a Local Area Network or a Metropolitan Area Network). One stumbling block in any new technology has been determining how to integrate the technology into a usable system and this paper admirably gives some food for thought. The second paper, by C. S. Brown, gives measured data from a coherent system proving that practical systems will indeed work with commercially available fiber. The third paper, by A. B. Bussard, presents the necessary optical fiber parameters which must be characterized to determine system performance. It is worth noting that optical fibers commercially available now are not characterized for coherent systems. The last paper, by S. Masuda, T. Chikama, and T. Touge, describes a component useful for coherent systems that is currently not available. The technical approach to produce this component adds to our fundamental knowledge of polarization preserving couplers.

In summary, this conference attempted to present the state of the art of an emergent technology in optical communications, one which is projected to progress rapidly, especially if commercialization takes place. The conference informs the reader of current research in the area of coherent communications and should help to stimulate new ideas in this area.

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Volume 568

Contents

COHERENT TECHNOLOGY IN FIBER OPTIC SYSTEMS

Volume 568

Session 1

Systems Issues

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Progress toward coherent fiber transmission

B. Basch, R. Kearns, G. Joyce, S. Stone, W. Chen

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Introduction

The use of optical fiber has revolutionized the communications industry during the few years in which it has been available, and still further advances are just over the horizon. Figure 1 shows five generations of optical fiber communication systems recognized today.[1] The increasing capabilities of each generation are characterized by significant increases in repeater spacing and channel capacity. The most advanced of these concepts is the use of heterodyne or homodyne detection of digital signals.

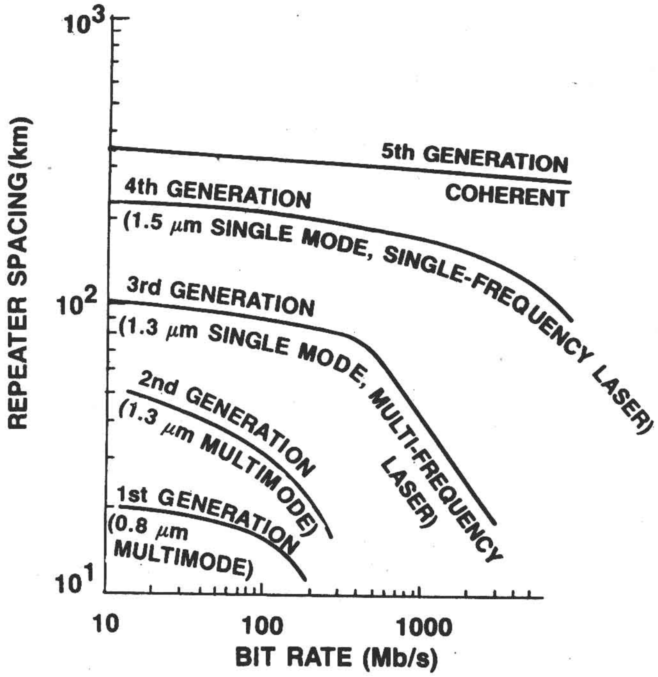

Figure 1. Performance of fiber optic systems.

Just as with RF and microwave communications, detection using a heterodyne or homodyne mixing process requires the modulation of a stable, narrow linewidth carrier; i.e., the requirements are those of a highly coherent source. The systems which use heterodyne or homodyne detection of optical signals are therefore referred to as coherent optical communication systems. The term coherent does not refer to the electrical demodulation, which may be either coherent (requiring phase estimation) or noncoherent. The remaining discussion will highlight the potential advantages of coherent optical communication as well as the difficulties encountered in practical implementation. Figure 2 shows a simple block diagram of a coherent fiber optic system.

An increase in receiver sensitivity of 14 to 20 dB can be realized over conventional direct detection schemes, representing increases in unrepeatered link lengths to 200 km or more. This technology, however, places a heavy burden on the electro-optic components used in these systems. The key word for these systems is stability. Coherent detection requires that a local oscillator be used to beat with the modulated signal in order to accomplish signal recovery. Figure 3 shows one way to accomplish this signal mixing. This local oscillator must be of the same frequency, with a possible offset, as the incoming signal and for some schemes must also be phase stabilized with that signal. Other advantages of coherent systems are a more efficient use of the optical waveguide bandwidth by utilizing sub-nanometer spacing of optical carriers and by the upgrading of existing systems by increasing the bit rate by a factor of from 8 to 10. This report will discuss the important parameters that must be satisfied in order to assure proper performance of the system.

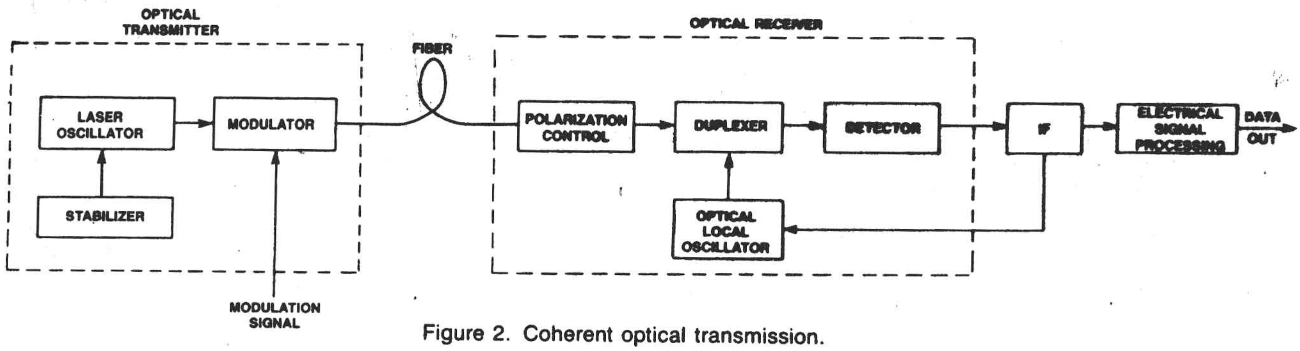

Figure 2. Coherent optical transmission.

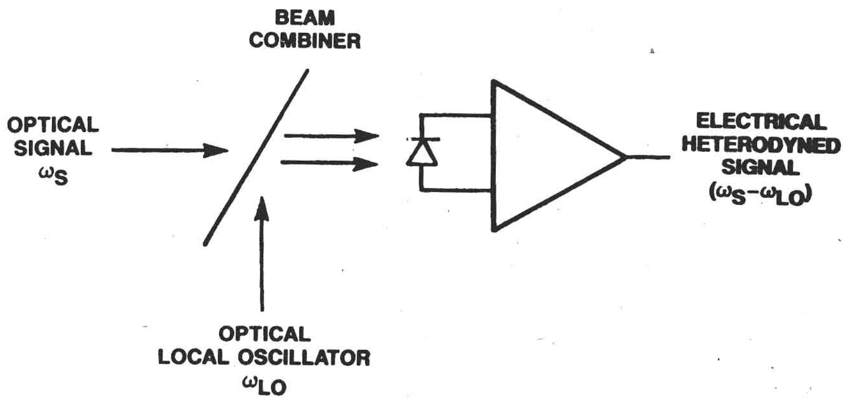

Figure 3. Optical heterodyning/coherent detection.

Systems considerations

Many different schemes can be used to implement a coherent transmission system.[2] In a homodyne system, the received signal is mixed with a local oscillator to produce a demodulated signal directly at baseband. For heterodyne systems, the local oscillator is displaced from the signal to produce a modulated beat frequency (intermediate frequency). Appropriate detection methods are then used to recover the modulation. There are three types of modulation that can be used in a coherent system.

- Amplitude Shift Keying (ASK)
- Frequency Shift Keying (FSK)
- Phase Shift Keying (PSK)

Figure 4 is a pictorial representation of the different types of coherent modulation. Along with each scheme is an associated theoretical sensitivity. The following table lists the number of photons per cell required for each type of system. The value for direct intensity modulation is included for reference.

It is interesting to note that direct detection appears to have a lower detection threshold than ASK and FSK. This would be true if quantum-limited detection were possible with direct detection; however, while it is possible to achieve quantum-limited performance in coherent systems, it is not possible with direct detection. For direct detection this would require a receiver with no thermal noise!

Homodyne detection requires that both the frequency and the phase of the signal and local oscillator be matched at the mixer. This generally leads to extremely severe source fabrication requirements. There are two possible approaches to optical homodyning.

1) Injection Locking

Any laser can be considered a multipass amplifier with a noise input. Control of the oscillation frequency therefore depends on maintaining a high cavity stability. However, if a sufficiently strong signal is injected, the frequency and phase of the output will follow those of the input. This allows for direct control of the local oscillator by the signal. Unfortunately, injection locking requires excessive power at the input, far exceeding the target sensitivity for homodyne systems.[3]

Table 1

Sensitivity of Optical Receivers

Modulation/Detection Type	BER	Number of Photons for BER of 10^{-9}, $\eta = 1$
ASK Heterodyne	$0.5\ \mathrm{Erfc}\left(\sqrt{\frac{\eta P_s}{4h\nu B}}\right)$	72
ASK Homodyne	$0.5\ \mathrm{Erfc}\left(\sqrt{\frac{\eta P_s}{2h\nu B}}\right)$	36
FSK Heterodyne	$0.5\ \mathrm{Erfc}\left(\sqrt{\frac{\eta P_s}{2h\nu B}}\right)$	36
PSK Heterodyne	$0.5\ \mathrm{Erfc}\left(\sqrt{\frac{\eta P_s}{h\nu B}}\right)$	18
PSK Homodyne	$0.5\ \mathrm{Erfc}\left(\sqrt{\frac{2\eta P_s}{h\nu B}}\right)$	9
Direct Detection		
Quantum Limit	$0.5\ \mathrm{Exp}\left(\frac{-\eta P_s}{h\nu B}\right)$	21
Practical Receiver		400–4000

The minimum Detectable (Peak) Power Level for a 10^{-9} Error Rate is Obtained by Multiplying the Number of Photons with $h\nu B/\eta$, Where B is the Bit Rate and η is the Detector Quantum Efficiency and $h\nu$ is the Energy of a Photon. P_s is the Peak Signal Power of the Received Signal.

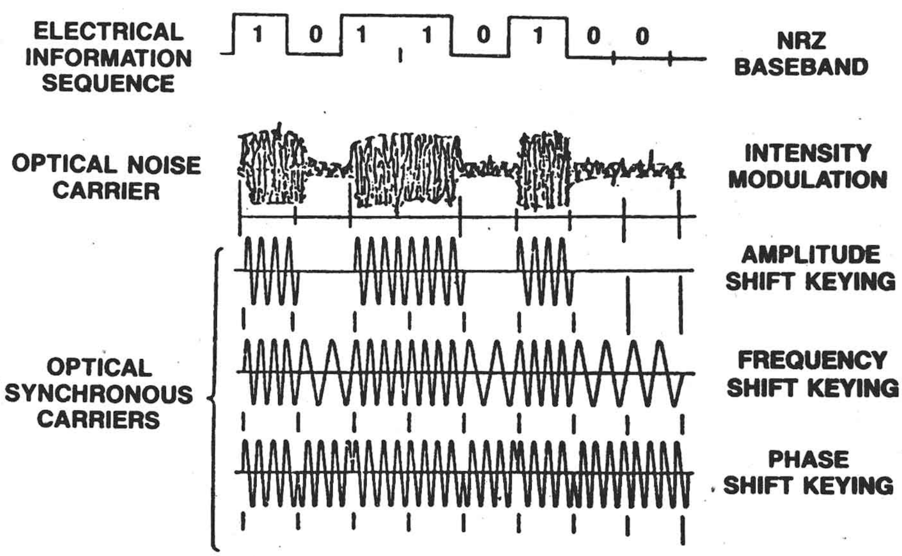

Figure 4. Modulation techniques.

2) Optical Phase Lock Loop

For an ordinary laser oscillator, a high cavity stability must be maintained in order to keep the frequency drift between the signal and local oscillator much less than the signal bandwidth and to provide phase estimation for coherent demodulation. It is possible to electrically detect the phase error between the signal and local oscillator and to use the error signal to correct the local oscillator frequency and phase.

Heterodyne detection requires that the frequency of the local oscillator be stabilized at some fixed offset compared to the signal. In general, it is easier to lock to this intermediate frequency than to lock to the optical signal as is done in homodyning. There are two methods for extracting the information from a heterodyne signal.

1) Coherent Demodulation

   Coherent transmission uses a second control loop to convert the intermediate frequency signal to baseband. Phase noise on the intermediate frequency, caused by local oscillator noise, can cause sensitivity degradation. However, this method can yield the largest signal capacity by utilizing frequency division modulation techniques.

2) Incoherent Demodulation

   Incoherent demodulation systems do not use the second control loop, but use the standard method of envelope detection in order to recover the signal. Although this results in the detection being less sensitive to phase noise, a slight penalty in sensitivity results.

System impairments

In order to achieve near quantum-limited performance, the strength of the local oscillator must be large enough to bring the mixed signal level well above the noise of the amplifier. Figure 5 shows a curve of receiver sensitivity power penalty for various input noise spectral densities as a function of local oscillator power. Below each noise current value is the equivalent resistor value assuming the amplifier to be resistor noise limited. With 50-Ω amplifier technology, a high level of oscillator power, greater than 5 mW, is required to keep the penalty below a few decibels. At modest bit rates, the oscillator power requirement can be reduced by using a high input impedance intergrating front end with equalization.

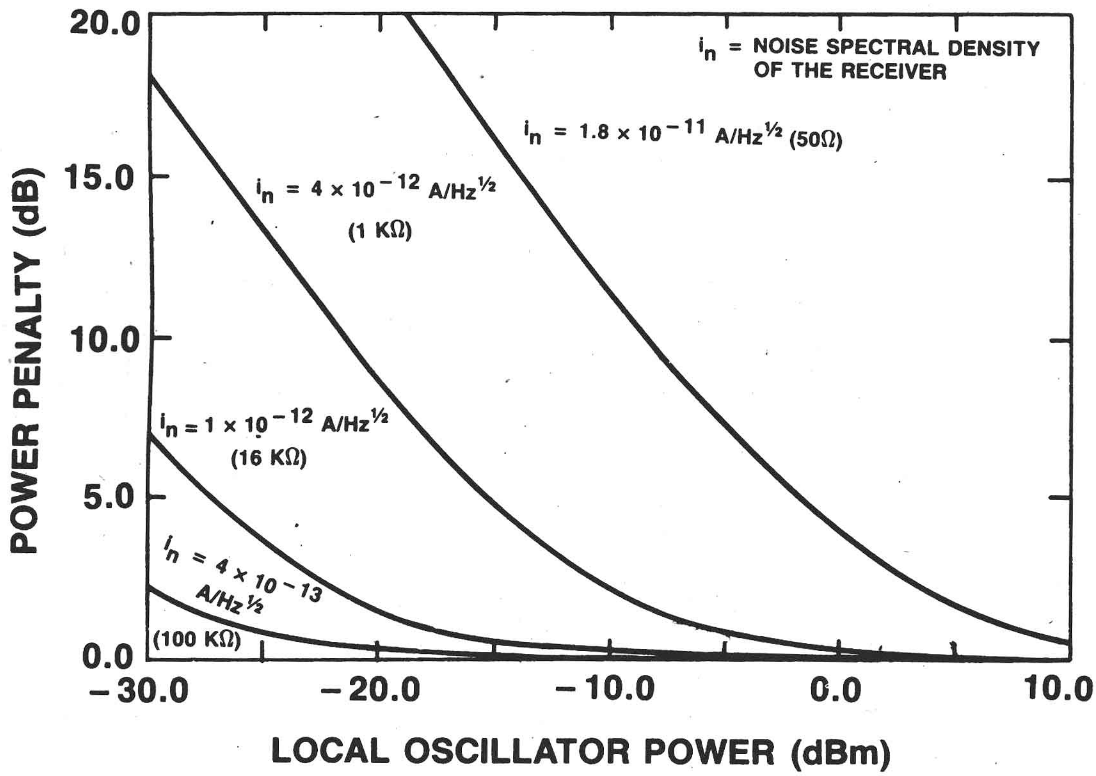

Figure 5. Dependence of coherent receiver sensitivity on local oscillator power.

For a PSK system, the probably of error can be expressed as:

$$P_e = \tfrac{1}{2} \int_{-\infty}^{\infty} p(\phi)\, \mathrm{Erfc}\left(\sqrt{SNR/2}\,\cos\phi\right) d\phi$$

The variable $p(\phi)$ is the probability function of the local oscillator phase variable ϕ, and the signal-to-noise-ratio (SNR) is the result of receiver noise. With the receiver SNR approaching infinity, an asymptotic value for the bit error rare can be obtained for a DPSK system.

Figure 6 shows a plot of the spectral width due to random phase changes vs the bit error rate floor. It will be noticed that the requirement on the spectral width of the source and local oscillator is more severe at lower bit rates. For example, for a bit rate floor of 10^{-9}, the spectral width should be about 1% of the bit rate. This corresponds to a spectral width of 10 MHz for a 1 Gb/s system or 0.1 MHz for a 10 Mb/s system. These two effects, receiver noise and phase noise, can be combined as shown in Figure 7. This figure shows the dependence of these parameters for system error rates 10^{-9} and 10^{-12}.

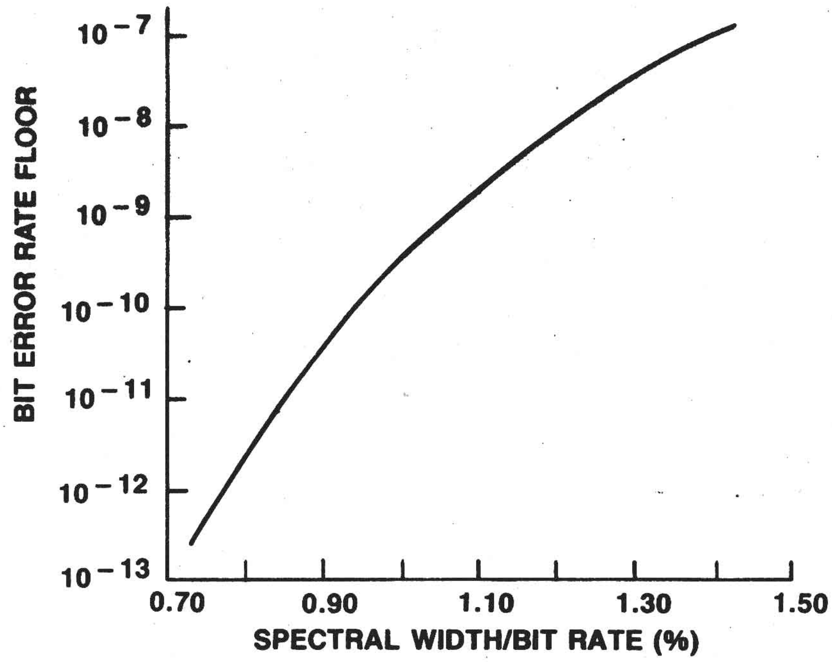

Figure 6. Dependence of BER on spectral width in DPSK system.

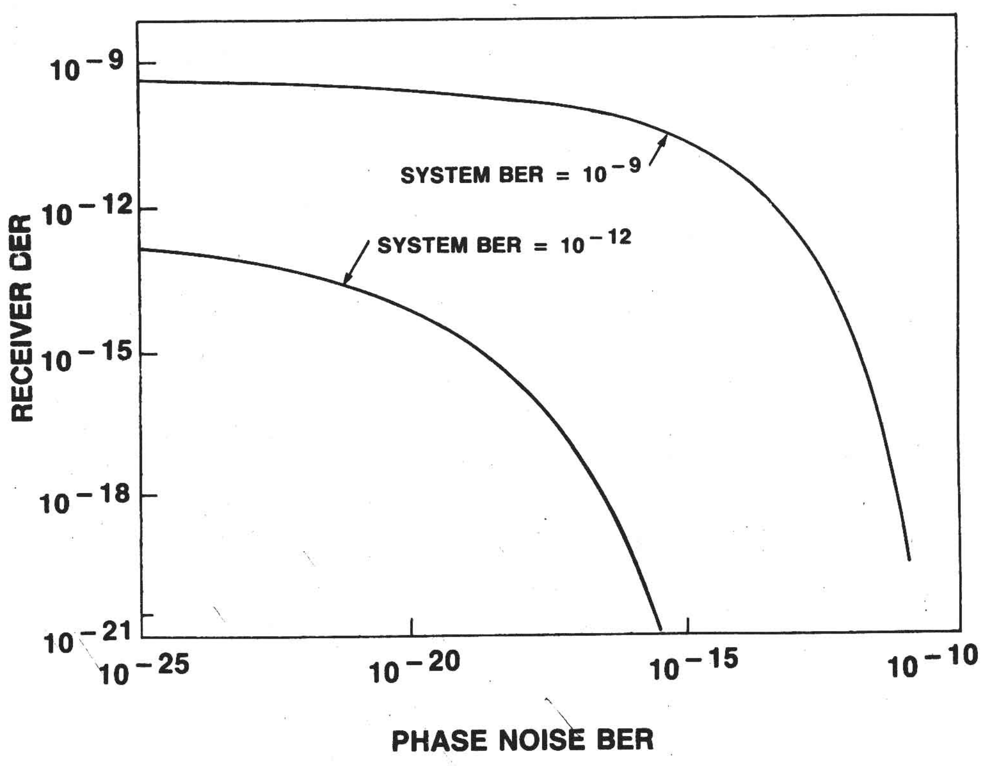

Figure 7. Dependence of system BER on receiver and phase noise.

In order to achieve heterodyne mixing, the state of the polarization of the signal must match the state of polarization of the local oscillator. If these two polarizations become misaligned, the IF signal fades. However, for ordinary single-mode fiber, the polarization state of light emerging from the fiber is randomized. The reason for this is that the two possible orthogonal polarizations propagate at different velocities (birefringence) and are randomly coupled along the fiber due to varying stress and temperatures. There are three common solutions to this problem.

One method utilizes single polarization single-mode fiber that supports only one propagating polarization state.[4] By properly aligning the fiber so that the orientation of the allowed propagation state matches the source at one end and the local oscillator light at the other end, the polarization fading is avoided. A high birefringence fiber that supports two polarization states can also be used because the propagation velocities of the two polarization states are so different that they are effectively decoupled from one another. As such, one of these states is selected to carry the signal and the other is not used. The fiber is then aligned, as was the single polarization fiber, such that the selected polarization state is aligned with both the source at one end and the local oscillator at the other end. The optical attenuation of both these types of fibers are higher, about 0.5 dB/km, thus both these methods of polarization control result in shorter repeater spacing.

A second method uses a polarization diversity receiver. The key point to understanding the polarization diversity receiver is that the incoming light can always be resolved into orthogonal components. These components have a slowly changing random relative phase, as well as slowly varying amplitudes. The local oscillator can also be split into corresponding orthogonal components. These two polarization components are independently mixed with the corresponding polarization components of the incoming light to yield two corresponding IF signals. These two IF signals are then combined via conventional diversity reception techniques. A procedure to implement such a system is shown in Figure 8. A phase comparator measures the relative phase between the two IF signals and generates a signal proportional to that phase difference. This feedback signal is sent to a phase shifter such that the two IF signals are brought into phase with one another. Having been brought into phase, these IF signals are then added to yield the composite output signal. In this receiver, the loss through the device can be anywhere from 0 to 3 dB, depending on the degree of polarization.

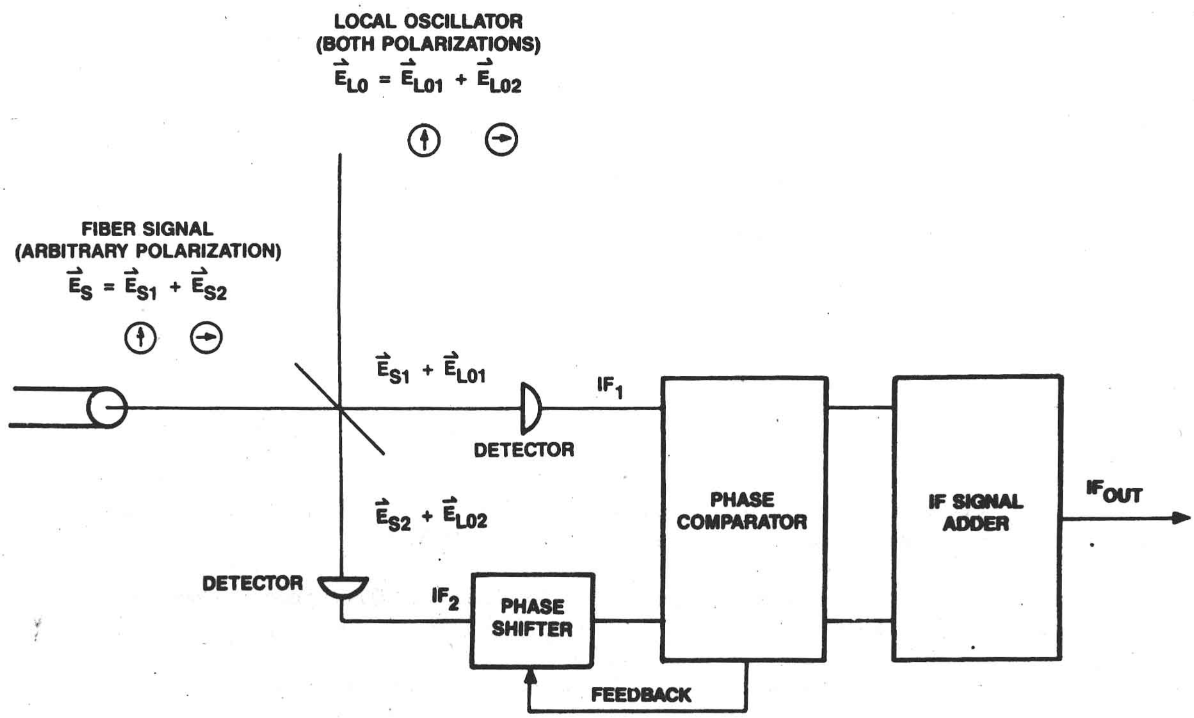

Figure 8. Polarization diversity receiver.

The third technique involves the utilization of a polarization correction device; that is, a device that will accept a signal of arbitrary polarization and convert it into the desired state of polarization, matching that of the local oscillator. Figure 9 is a representation of such a scheme. The quarter wave plate is aligned to convert the elliptical light to linearly polarized light, while the half wave plate is used to rotate the linearly polarized light so that it matches that of the local oscillator. The quarter and half wave plates are actuated by optical/electronic/mechanical feedback mechanisms with finite response times. As such, this method relies on the fact that the polarization changes slowly.

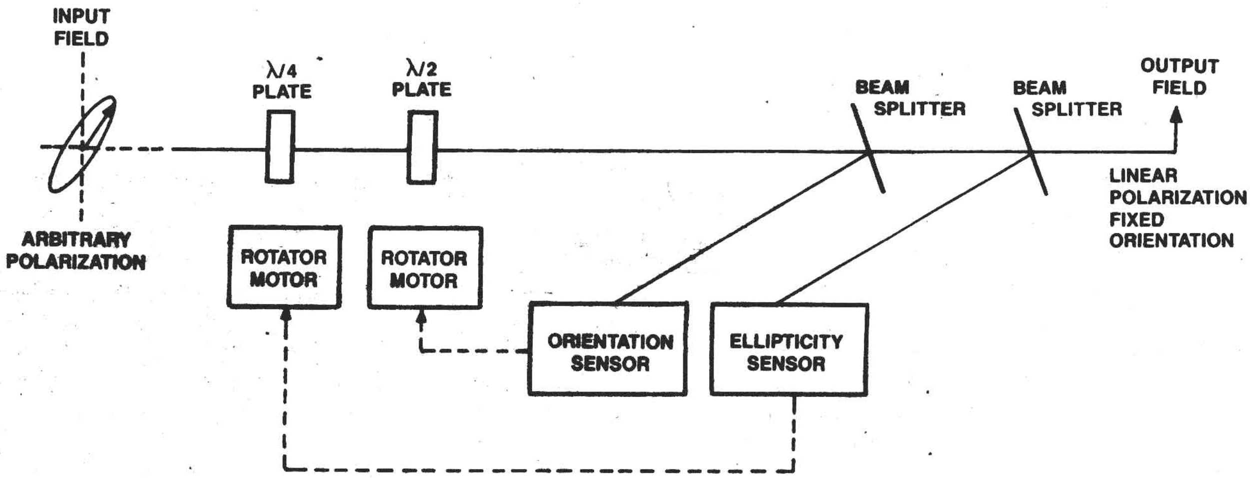

Figure 9. Discrete component polarization controller.

Conclusion

The early results of coherent transmission experiments are extremely encouraging. Improvements in receiver sensitivities of from 14 to 20 dB can be expected with coherent techniques over direct detection methods. Coherent techniques also allow frequency division multiplexing with very fine carrier separation which results in a large increase in transmission capacity. Issues that must be addressed are practical and simple techniques to control laser stability and the development of narrow linewidth lasers. Methods to handle polarization fading must be studied and practical solutions found.

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Optical Sources for Coherent Optical Fiber Communication Systems

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Abstract

This paper reports recent progress in the development of three categories of optical sources with linewidths, $\Delta\nu$, sufficiently narrow to be used in heterodyne and homodyne optical fiber communication systems: First, single-longitudinal-mode semiconductor lasers with relatively broad linewidths of several tens of MHz, suitable for amplitude-shift-keying and frequency-shift-keying heterodyne with envelope detection. Second, semiconductor lasers with weak optical feedback having $\Delta\nu \approx 1$ MHz. Such narrow linewidth sources would be required for differential-phase-shift-keying heterodyne detection. Third, semiconductor lasers with strong optical feedback, and 1523 nm He-Ne lasers, both having $\Delta\nu \leq 15\, kHz$, Such very narrow linewidth sources would be required for PSK homodyne detection.

Introduction

Optical heterodyne and homodyne detection techniques have the potential for 10 to 20 dB improvement in receiver sensitivity as compared to direct detection.[1] In addition, tunable local oscillator (LO) lasers would offer the ability to demultiplex channels with a frequency separation of only a few GHz. These two features have significant value to the telephone exchange and local distribution network allowing new networking capability and increasing channel capacity.

A major obstacle to the development of coherent optical fiber communication systems has been the difficulty of obtaining sufficiently narrow linewidth sources at wavelengths near 1300 and 1550 nm, which correspond to the low loss windows of silica fibers. The recent achievement of single-longitudinal-mode (SLM) semiconductor lasers at these wavelengths has led to transmission experiments using amplitude-shift-keying and frequency-shift-keying with envelope detection (ASKE and FSKE) at 100 Mb/s[2,3] and most recently FSKE at 560 Mb/s[4]. These experiments used distributed feedback (DFB) lasers having relatively broad linewidths of several tens of MHz. Sources with narrow linewidths on the order of 1 MHz have been achieved by placing SLM semiconductor lasers in external cavities.[5,6] Such sources were used in a differential-phase-shift-keying (DPSK) heterodyne detection experiment at 200 Mb/s.[7] Very narrow linewidths on the order of 15 kHz have been achieved by placing an antireflection coated semiconductor laser in an external cavity with strong optical feedback[8,9] and from 1523 nm He-Ne lasers.[10] A transmission experiment at 140 Mb/s using PSK homodyne detection was carried out using 1523 nm He-Ne lasers.[11] Recent progress in the realization of broad, narrow and very narrow linewidth lasers and their suitability for optical heterodyne or homodyne detection will be discussed below.

Broad linewidth lasers

The linewidth of SLM semiconductor lasers is typically 100 MHz at 1 mW output power per facet. The relatively large linewidth is due to the change of refractive index with carrier density, which couples phase and intensity fluctuations arising from spontaneous emission. Henry has shown that the linewidth can be expressed as[12]

$$\Delta\nu = \frac{V_g^2 h\nu g n_{sp} \alpha_m \left(1 + \alpha^2\right)}{8\Pi P} \qquad (1)$$

where h is the Planck constant, ν the lasing frequency, V_g the group velocity, g the medium gain, α_m the mirror loss, n_{sp} the spontaneous emission factor and P the power emitted per facet. The factor $(1 + \alpha^2)$ is the linewidth enhancement factor, where $\alpha = \Delta n'/\Delta n''$, and $\Delta n'$ and $\Delta n''$ denote the change in the real and imaginary parts of the refractive index due to the change in carrier density after a spontaneous emission event. Experimentally, α is found to be in the range of -2.2 to -6. The 1/P dependence of $\Delta\nu$ has been verified for most SLM semiconductor lasers.

Kazovsky has calculated the required linewidth-to-bit rate ratio, $\Delta\nu/B$, for several types of optical heterodyne receivers.[13] The results for ASKE and FSKE are:

$$\text{ASKE} \qquad \Delta\nu/B \leq 0.09 \tag{2a}$$

$$\text{FSKE} \qquad \Delta\nu/B \leq 0.08\,(f_d/B)^2 \ \text{if}\ f_d/B < 1.54 \tag{2b}$$
$$\leq 0.09 + 6\,(f_d/B) \ \text{if}\ f_d/B \geq 1.54$$

where $\Delta\nu$ is the linewidth, B the bit rate and f_d the frequency deviation. These results assume two performance criteria: First, the degredation of the signal-to-noise ratio at the output of the IF amplifier is less than 1 dB. Second, the bit-error-rate (BER) floor due to phase noise is less than 10^{-10}. Typical SLM lasers emitting a relatively low power of a few mW should satisfy the linewidth requirement for ASKE and FSKE detection at a bit rates above several hundred Mb/s.

Recently, FSKE single filter detection has been demonstrated for the first time at 560 Mb/s using broad linewidth DFB lasers.[4] Figure 1 shows the intermediate frequency (IF) spectrum obtained by heterodyning two DFB lasers similar to those described in Ref. 14, each emitting about 2 mW. The linewidths of the source and LO lasers were 10 MHz and 40 MHz, respectively, leading to an IF linewidth of about 50 MHz. Figures 2a and 2b show the IF signal and the output of the envelope detector. In this experiment a wide frequency deviation of 2.5 GHz due to direct current modulation of 8 mA pp was used to ensure a clean separation between spaces ("0's") and marks ("1's").

FSK systems have the attractive feature that the source laser can be directly modulated through injection current modulation. The current/frequency-modulation transfer function, $\Delta f/\Delta i$, should ideally be constant throughout the baseband frequency range. Nonuniformity of the diode laser frequency modulation (FM) response due to thermal effects can cause severe distortion of the optical FSK signal for modulation frequencies below about 1 MHz. Manchester coding[3] and equalization of the laser drive signal[15] have been employed to achieve FSK transmission at 100 Mb/s. The thermal FM effect may be of less concern at higher bit rates, since a smaller fraction of the baseband spectrum lies below 1 MHz. This is demonstrated in Figures 3a and 3b, which show demodulated FSK waveforms for 560 Mb/s NRZ pseudo-random modulation of a vapor-phase-transported (VPT) DFB laser[16] with 2^7-1 and $2^{15}-1$ bit sequences, respectively. The lower trace shows a slight frequency chirp during long strings of "0's" and "1's" due to thermal FM. However, no chirp is seen for the shorter bit sequence (upper trace). Figure 3c shows the "eye diagram" from the output of the FSK envelope detector for 560 Mb/s NRZ 2^7-1 pseudo-random modulation. In practical transmission systems, long strings of "0's" or "1's" are avoided, either by scrambling or special line codes (e.g., 5B6B block code). Our results show that for the VPT-DFB laser, FM due to thermal modulation is not a serious limitation for FSK transmission at bit rates above 560 Mb/s.

Optical reflections can dramatically affect the optical spectrum of SLM lasers. Our experience with DFB lasers coupled to single-mode fibers (SMF) was that at least 30 dB of optical isolation was needed to attain a stable IF spectrum. With less optical isolation, both the source and LO laser exhibited mode hopping among external cavity modes apparently due to reflections from the SMF coupler used to combine the two laser outputs. Thus, it appears that low cost optical isolators will be needed components for heterodyne systems using broad linewidth SLM semiconductor lasers.

Narrow linewidth sources

The linewidth of semiconductor lasers can be significantly reduced using weak optical feedback from an external reflector. Patzak et al.[17] have shown that a complete description of the line-narrowing characteristics in the weak feedback limit includes not only an equation for the linewidth reduction factor $\Delta\nu/\Delta\nu_o$, but also equations for the frequency deviations, Δf, for the modes induced by the external cavity from the solitary laser frequency f_o, and an equation for the normalized threshold reduction $\Delta I_{th}/\Delta I_{th,max}$ of the external cavity modes:

$$\frac{\Delta\nu}{\Delta\nu_o} = \frac{1}{[1+X\sqrt{1+\alpha^2}\cos(2\Pi(f_o+\Delta f)\tau_e - \tan^{-1}\alpha)]^2} \tag{3}$$

$$2\Pi\Delta f\tau_e = -X\sqrt{1+\alpha^2}\sin(2\Pi(f_o+\Delta f)\tau_e - \tan^{-1}\alpha) \tag{4}$$

$$\frac{\Delta I_{th}}{\Delta I_{th,max}} = -\cos(2\Pi(f_o+\Delta f)\tau_e) \tag{5}$$

where $\Delta\nu_0$ and f_0 are the linewidth and frequency of the solitary laser, X is the feedback parameter given by $X = \sqrt{\eta}\,\tau_e/\tau_d$, η is the fraction of output power coupled back into the laser, and τ_e and τ_d are the roundtrip times in the external cavity and diode cavity, respectively. Assuming a typical value of $\alpha = -5.3$, it was shown that the maximum linewidth reduction lies between $(1 + X\sqrt{1+\alpha^2})^{-2}$ and $[1 + X]^{-2}$, with a transition from the former for $X \leq 1$ to the latter for $X \geq 10$. For example, with $\eta = 10^{-4}$ and $\tau_e/\tau_d = 200$ (~20 cm external cavity length), X = 2 and the maximum linewidth reduction factor would be about 8×10^{-3}. The feedback narrowed linewidth would be less than 1 MHz for a solitary laser linewidth of 100 MHz at 1 mW.

Kazovsky has calculated the linewidth requirement for DPSK heterodyne detection using the same performance criteria discussed above. His result is that $\Delta\nu/B < 0.007$.[13] This limit suggests that semiconductor lasers with external cavities can be used for DPSK detection for bit rates above 100 Mb/s. This has been confirmed by the recent demonstration of DPSK detection at 200 Mb/s using distributed Bragg reflector (DBR) lasers in external cavities for both the source and LO.[7]

Figure 4 shows the delayed self-heterodyne[18] (DSH) spectrum measured for a 1300 nm C^3 laser placed in a 60 cm long external cavity with $\eta = -42$ dB. A schematic of the DSH measurement apparatus is shown in Figure 5. The fiber delay line was 6 km, giving a linewidth resolution limit of $(2\tau_{fiber})^{-1} \approx 15$ kHz. In this example, the laser linewidth is 500 kHz at 2 mW output power, as compared to 100 MHz without feedback. The lasing wavelength of the C^3 laser could be step-wise tuned among 6 longitudinal modes by adjusting the current in the rear cavity. For each new wavelength, it was necessary to readjust the phase of the feedback to get the minimum linewidth. Linewidth narrowing was also observed for a multimode laser in a 15 cm long external cavity. Figure 6a shows the DSH spectrum and longitudinal mode spectrum for a 1300 nm multimode laser with weak optical feedback. The minimum linewidth was less than 1 MHz. It was also observed that under certain optical feedback conditions essentially SLM output was achieved, as shown in Figure 6b. These results suggest the possibility that conventional multimode semiconductor lasers in external cavities could be used for heterodyne detection.

From Eqn. (3) - (5), the linewidth, frequency, and mode intensities of a semiconductor laser with weak external feedback can be very sensitive to the phase of the feedback. The effect of feedback phase on linewidth is demonstrated in Figure 7, which shows the DSH spectrum measured for the C^3 laser in a 20 cm long external cavity. With $\eta = -50$ dB, the minimum linewidth was 10 MHz (top trace). The linewidth broadened dramatically as the feedback phase was changed (bottom trace). Also for this case the dominant mode frequency changed by several hundred MHz and the output became multimode as the phase was changed from the narrow linewidth condition. With the 60 cm external cavity and $\eta = -42$ dB, the linewidth of 500 kHz (Figure 4) was essentially unchanged as the feedback phase was varied. However, the dominant mode frequency and side mode intensities were similarly affected by the feedback phase. Therefore, some sort of control of the feedback phase would be needed in order to maintain a narrow linewidth, together with a stable frequency and single-mode output.

Another potential difficulty with external cavity lasers is the need for external modulation. Amplitude and phase modulators with modulation bandwidths of several GHz have been made by diffusing waveguides an electrooptically active substrate, such as $LiNbO_3$. Fiber-to-fiber insertion losses as low as 2.9 dB have been obtained together with optical return losses as high as 35 dB.[19] In addition, the planar geometry of such integrated optic devices lends itself to automated, high volume processing.

Very narrow linewidth sources

Optical homodyne receivers are expected to have the following important advantages with respect to optical heterodyne:[20] 1) 3 dB sensitivity improvement in terms of signal power, 2) higher bit rate with the same detector bandwidth, 3) simpler post detection processing since the IF part is eliminated, and 4) readily available direct detection receivers can be used for construction of homodyne receivers. These advantages of homodyning over heterodyning will be increasingly important as bit rates increase. However, homodyne will require the use of optical phase-locked loops (OPLL) which will impose the most stringent linewidth requirements of the various heterodyne and homodyne detection techniques. Kazovsky has estimated the PSK homodyne linewidth requirement to be $\Delta\nu/B \leq 8 \times 10^{-5}$.[20] Thus, lasers with linewidths on the order of 10 kHz will be needed for PSK homodyne at bit rates above 100 Mb/s.

The fundamental linewidth of a He-Ne laser is less than 1 Hz. However, acoustic disturbances of the cavity length are expected to produce frequency jitter having a spectral width of a few kHz. Figure 8 shows the DSH spectrum measured for a 1523 nm He-Ne laser. This result confirms that the time average spectral width is less than the DSH resolution limit of 15 kHz.