Recent Advances in Coherent Optical Fiber Communication Systems

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Abstract—Research and development of coherent optical fiber communications have been accelerated mainly because of the possibility of receiver sensitivity improvement reaching 20 dB, and partly because of the possibility of frequency-division multiplexing (FDM) with very fine frequency separation. In this paper, recent advances in the research on coherent optical fiber communication systems are reviewed, with emphasis on those reported in the past two years. The bit-error rate measurements so far reported are classified and investigated in four categories: PCM-ASK, PCM-FSK, PCM-PSK, and PCM-DPSK. The states-of-the-art of polarization-state stabilization techniques is also discussed.

I. INTRODUCTION

Since the earliest papers on heterodyne (or homodyne) and coherent optical fiber communications appeared in 1979 in Japanese [1], [2] and in 1980 in English [3]-[5], the research in this area has expanded year by year. It is now performed in almost all of the major communications laboratories in the world. This is mainly because of the possibility of receiver-sensitivity improvement reaching 20 dB [3]-[7] and partly because of the possibility of frequency-division multiplexing (FDM) with very fine frequency separation, typically 10-100 GHz [3].

The research on the heterodyne (homodyne)/coherent optical fiber communications can be classified into three categories:

1) Theoretical analysis of the system including the transmitter, fiber waveguide, and receiver. The noise phenomena in the system, bit-error rate (BER) improvement, and polarization fluctuation in the fiber lightguide have been the principal concern of the researchers.

2) Research and development of special devices required in the coherent systems, such as frequency-stabilized and spectrum-purified lasers, polarization-maintaining fibers, polarization-state controllers, coherent modulators, heterodyne or homodyne detectors, and demodulators.

3) System experiments including bit-error rate (BER) measurements and the development of polarization-control schemes.

In the short history of the research in this area in 1979-1985, efforts were first paid to the theoretical system analysis (item 1), and then to the improvement of the devices (item 2). On the other hand, since late in 1981, reports began to appear on the bit-error rate (BER) measurement of heterodyne (homodyne)/coherent optical fiber communication systems, taking advantage of the device technologies newly developed for such systems. In the same period, various polarization-control schemes were also developed.

The purpose of this paper is to review the recent advances in such systems research. The progress of the relevant device technologies have been reviewed in many tutorial/review papers [8]-[15], whereas the progress in the relevant BER theories and BER measurements have been summarized also in some of the previous review papers [5]-[7], [15]-[17]. Therefore, as to the BER measurements, emphasis will be placed upon the achievements in the past two years. Recent achievements in the polarization-control schemes will also be described, but rather briefly because of space limitations.

II. DEFINITION OF "COHERENT" COMMUNICATIONS

The term "coherent" in the title of this paper needs explanation. Presently the term "coherent" seems to be used in two different meanings. In the first meaning, a PCM-on-off keying (OOK) heterodyne system is classified in "noncoherent heterodyne" systems, whereas a PCM-phase-shift keying (PSK) heterodyne system is classified in "coherent heterodyne" systems. In the second meaning, the PCM-OOK heterodyne system is also considered as "coherent" because, on the surface of the frequency mixing diode in this system, we take advantage of the spatial coherence of the carrier. In the title of this paper, the word "coherent" is used in the second meaning; i.e., we consider that all heterodyne and homodyne schemes are coherent schemes.

III. IMPROVEMENT OF EQUIVALENT RECEIVER SENSITIVITY BY COHERENT MODULATION/DEMODULATION SCHEMES

The greatest advantage of the coherent schemes is the improvement of the equivalent receiver sensitivity, that
is, the reduction of the minimum receiving signal level for achieving a prescribed BER, for example, $10^{-9}$.

As has been described in detail in previous papers (e.g., [17]), this sensitivity improvement is attributed to two effects. One is the improvement of the S/N at the output end of the receiver preamplifier (for a given signal level) by the use of the heterodyne or homodyne detection, as compared with a direct detection. The amount of this sensitivity improvement is typically 10–20 dB at wavelengths of 1.3–1.6 µm [6], [17].

The other effect is the improvement of the BER (for a given S/N) brought about by the use of a coherent modulation/demodulation scheme (PSK and FSK) as compared with a noncoherent (OOK) scheme. The amount of this improvement reaches 3–9 dB, depending upon the type of modulation and demodulation [6], [7], [17], as shown in Fig. 1.

IV. FREQUENCY-SELECTIVITY IMPROVEMENT BY HETERODYNING

The second advantage of a heterodyne (or homodyne) system is that the frequency selectivity can be improved because of the good frequency selectivity of the intermediate frequency (IF) amplifier, which is much sharper than that of an optical filter. Thus, FDM schemes with very fine carrier separation become possible [3]. This allows, for example, an efficient use of the minimum dispersion wavelength region (1.3-µm region) of silica-glass optical fibers.

However, in the present state-of-the-art, this advantage cannot be emphasized for a long-haul telecommunication system, because the optical power loss in the optical multiplexer at the transmitting end and demultiplexer at the receiving end will not be negligible, when the frequency separation between carriers is small.

Fig. 2 illustrates the problem. Fig. 2(a) shows an example of the carrier frequency allotment in a superwideband FDM system discussed in one of the earliest papers [1]. In this case ten carrier frequencies are arranged with 100 GHz separation in each carrier group (corresponding to the passband of an optical branching filter) having 2-THz bandwidth. Fig. 2(b) shows how the ten carriers are divided into ten heterodyne receivers. If the power divider in Fig. 2(b) has no frequency selectivity, all the signals will undergo an appreciable branching loss, i.e., at least 10-dB loss when ten carriers are divided into ten receivers.

Such a branching loss is more or less inevitable in the present state-of-the-art. In the near future, however, optical branching filters with 100-GHz separation (or even 10-GHz separation) might become possible by new schemes such as fiber-type double-path filters [18].

Some specialists assert, on the other hand, that we may take advantage of the fine frequency selectivity of the heterodyne system in some applications even within the present state-of-the-art; these applications are superwide band local area networks (LAN’s), CATV networks, and integrated-services subscriber networks to be realized in the future. Note that the multiplexing/demultiplexing loss is not very serious in such short-haul systems.

V. BIT-ERROR RATE (BER) MEASUREMENTS

The first report of BER measurement appeared in 1981. Since then more than twenty papers describing BER measurements have been published; Tables I–IV summarizes these reports in four categories: PCM-ASK, PCM-FSK, PCM-PSK, and PCM-DPSK, each in chronological orders. Table V summarizes these reports to show the general trends in the research. The investigation of the reports may not be thorough, particularly for 1984 and 1985. A remarkable fact, however, is that the researchers’ concern has been moving from ASK to more sophisticated FSK, PSK, and DPSK.
In the following, the technical significance of these papers, in particular those appearing in the past 24 months, are described. Papers published before the middle of 1983 have been tabulated, and their significance discussed, in another review paper [17].

A. BER Measurements of ASK Heterodyne/Homodyne Systems (Table I)

Significant recent trends (after 1983) are the uses of LiNbO₃ waveguide-type external modulators in [A5], [A6], and the use of DFB laser diodes both as the transmitter and the local oscillator. These new trends have altogether brought forth high bit-rate modulation and long transmission distance. However, the potential of the reports in this category is decreasing.

B. BER Measurement of FSK Heterodyne Systems Including a PSK-FM System (Table II)

In this category many reports have appeared in the past two years. A PCM-PSK-FM system using a 280 MHz subcarrier [F3] seems to aim at a preliminary experiment for FDM wideband LAN’s to appear in future. Direct frequency modulation of a DFB laser diode [A4] or a double-channel planar buried heterojunction (DCPBH) laser diode with an extended (10 cm long) cavity resonator [A5] are new trends aiming at the dynamically single-mode directly-modulated transmitter.

The use of a new scheme called single-filter FM detection [F4], the achievement of 200-km transmission distance [F5], and BER measurement at a very high bit-rate (560 Mbit/s; [F6]) are the noticeable new achievements.

After Table II was completed, another latest report on BER measurement on an FSK system from Yokosuka NTT, drew the author’s attention [F7]. It describes a BER measurement using 1.5-μm DFB laser diodes with extended cavities, 8 cm and 10 cm long for the transmitter and local oscillator, respectively.

C. BER Measurements of PSK Heterodyne/Homodyne Systems (Table III)

Two of the recent papers [P4], [P6] dealt with PSK homodyne systems. The technical tasks are fairly different for the PSK heterodyne and PSK homodyne systems, because an optical phase-locked loop (OPLL) technique is needed in the homodyne systems, whereas the phase locking can be achieved at the intermediate-frequency stage in heterodyne systems.

The paper given in [P4] was the first to report the homodyne detection of a signal transmitted over a long distance (30 km), but using HeNe gas lasers for both the...
transmitter and local oscillator. The homodyne detection of a signal transmitted over a long distance has not successfully been achieved with semiconductor lasers.

D. BER Measurement of DPSK Heterodyne Systems (Table IV)

Improvement of spectral purity of lasers (transmitter and local oscillator) by extended-cavity (30 cm long) scheme [D5], and experiment at very high bit-rate (400 Mbit/s; [D6]), are the noticeable new achievements.

VI. SPECTRAL PURITY OF LIGHT SOURCES

As has been predicted by theory (see Fig. 1), the PSK homodyne system has exhibited the highest receiver sensitivity, i.e., the lowest signal level to achieve a prescribed BER. The greatest sensitivity improvement so far observed reaches 19 dB [P1] with a PCM-PSK “self-homodyne” setup, i.e., using a single HeNe gas laser as both the transmitter and local oscillator. However, it is speculated that gas lasers would not be used in practical systems because of their large size, poor efficiency and short life. Semiconductor lasers will probably be used despite their relatively poor spectral purity, i.e., large linewidth. This speculation has stimulated the research on the effect of phase noise of lasers on the BER.

So far the BER theory of coherent optical communications has been advancing in the following three steps: 1) BER theories assuming purely monochromatic carrier (~1980) [5]–[7], 2) BER theories considering linewidth of carrier (and local oscillator) originating from white frequency-noise spectrum (~1983) [P2] [19], and 3) BER theories considering also the effect of 1/f frequency-noise spectrum (~1985) [20].
In the above second stage, the estimated requirement for the linewidth was severe; it was estimated that the linewidth must typically be less than 1 MHz for a PCM-PSK system to achieve BER = 10^{-9} at a bit rate of 32 Mbit/s. However, it was found recently that the spectral broadening of DFB semiconductor lasers operating at high power level is principally due to the 1/f-type FM noise [20]. It is also predicted theoretically that when the 1/f-type FM noise is predominant, the apparent linewidth requirement is much lightened (e.g., one order of magnitude). This is because when the linewidth is mainly due to low-frequency FM noise, its effect is much less harmful than an equal linewidth produced by a white FM noise. Moreover, the linewidth could also be reduced by feedback techniques when low-frequency component is predominant.

VII. POLARIZATION-STATE CONTROL SCHEMES FOR HETERODYNE OR HOMODYNE OPTICAL FIBER COMMUNICATIONS

A. Countermeasures Against Polarization-State Fluctuation

In an optical heterodyne (or homodyne) receiver, and/or when an optical IC is used in the receiver, the fluctuation of the polarization state in the fiber may deteriorate the receiver sensitivity. In such cases, therefore, a polarization-state control scheme is indispensable [12]. The complete solution to this problem will be the use of a polarization-maintaining fiber over the entire length of the communication channel (see [21], and for a more up-to-date review [22]). However, the polarization-maintaining fiber is still technologically at a premature stage, and can not be used in practical communications at reasonable cost.

Two alternative countermeasures are:

1) the use of a polarization-state control device at receiving end, which matches the local oscillator (LO) polarization state with that of the signal [23], and

2) the use of a polarization-diversity receiver, in which two orthogonal polarization components of the received signal are detected separately and added later (in a heterodyne receiver, at its intermediate frequency (IF) stage) after an appropriate phase compensation [24].

In addition, various versions and combinations of these two basic schemes are being investigated.

In this paper various polarization-state control schemes proposed so far are compared, and their features are compared.

B. Classification and Principles of Various Polarization-State Control Schemes

All of the polarization-state control schemes so far proposed consist basically of two controlling elements, because the number of freedom of a polarization state is two, i.e., the ellipticity and deflection angle. The controlling elements used in the six schemes proposed so far are, in a chronological order, electromagnetic fiber squeezers [25], electrooptic crystals [26], [27], rotatable fiber coils [28], rotatable quarter-wave and half-wave plates [29], Faraday rotators [30], and rotatable fiber cranks (RFC's) [31]. These six schemes are tabulated in Table VI.

1. Electromagnetic Fiber Squeezers: In the first proposal of this sort, two electromagnetic fiber squeezers were used as the polarization-state conversion elements [25]. In this scheme two electromagnets give transverse stress to the fiber in the directions of 0° and 45°, so that the polarization state becomes (for example) horizontally polarized at the exit of the second squeezer. The control signals for the electromagnets are obtained from four polarization components (0°, 45°, 90°, and 155°) measured at the exit; these are used to compute the currents to be fed to the electromagnets.

2. Electrooptic Crystals: Shortly after Ulrich's proposal, Kubota et al. reported an electrooptic equivalence of the electromagnetic fiber squeezers. In this scheme [26], [27], the first electrooptic crystal converts, by controlling the voltage applied to the crystal (and hence its birefringence), the incident polarization state to an "upright" elliptical polarization. Next, by controlling the birefringence of the second electrooptic crystal which is tilted by 45°, we can convert the polarization state to a linear polarization in the horizontal or vertical direction.

3. Rotatable Fiber Coils: The device invented by Lefevre [28], called here tentatively rotatable fiber coils, is based upon a somewhat different principle. The first coil gives, by bend-induced birefringence, a 90° phase difference to two orthogonal modes, whereas the second coil gives a 180° phase difference. Any elliptical polarization can first be converted, by adjusting the tilt angle of the first coil, to a tilted linear polarization. It can then be rotated to another linear polarization with an arbitrary angle by controlling the tilt angle of the second coil, because a rotatable 180° phase plate functions as a simple deflection-angle rotator for a linearly polarized incident light.

4. Rotatable Phase Plates: Recently Imai et al. [29] reported a new scheme in which quarter-wave and half-wave plates are used in place of the rotatable fiber coils.
The principle of its operation is entirely identical to that of the Lefevre's device. However, the phase plates have a great advantage in that the rotation is endless, in contrast to the limited tilt angle in the Lefevre's device.

5. Faraday Rotators: In the new scheme called Faraday-rotator device [30], two Faraday rotators are connected in cascade, with a coil of fiber between them. When a light having an arbitrary elliptical polarization is incident, we can set it upright at the exit of the first rotator by controlling the current flowing in it. Then the light passes through a fiber coil which gives a 90° phase difference between the x- and y-polarizations to produce a linearly polarized light at its exit. Finally, this linear polarization is rotated to horizontal (or vertical) polarizations at the exit of the second Faraday rotator by controlling the current flowing in it.

6. Rotatable Fiber Cranks: In this scheme [31], the polarization-state control device consists of two fiber elements, each of which is made by bending a short fiber section in a crank form, as shown in Fig. 3(a). This scheme features a negligibly small insertion loss and a capability of an endless control of polarization state like in the rotatable phase plate.

If a short fiber is bent in a crank form (Fig. 3(a)), linear birefringence will be induced between x- and y-axes. When such a crank element is rotated around the axis A-C (see Fig. 3(b)) giving only "translation" movement to the fiber at point B, the principal axis of bending birefringence also rotates without changing its magnitude. Hence, if we choose an appropriate fiber length 2f and shape so that the bending birefringence $\Delta \beta = \pi/2$ or $\pi$, we can obtain a device equivalent to a quarter-wave plate or a half-wave plate, which have been used in the polarization-state control scheme by Imai et al. [29].

C. Features of Various Polarization-State Control Schemes

It has been confirmed experimentally that all of the above schemes function satisfactorily as to the compensation of the polarization-state fluctuations. However, these schemes have different features as to the following technical requirements: 1) insertion loss, 2) endlessness in control, 3) temporal response, and 4) presence or absence of mechanical fatigue.

1. Insertion Loss: The requirement for low insertion loss can practically be satisfied only by all-fiber-type devices. This is because a polarization-state controller is most probably used in a single-mode fiber circuit. Only an all-fiber-type device can be coupled to input and output fibers with low insertion loss ($\sim 0.2$ dB) by splicing.

2. Endlessness in Control: This is an important requirement, because "resetting" might become necessary in those attempts in which the control range is limited. Among those devices so far reported only the phase-plate scheme and rotatable fiber cranks can satisfy this requirement.

3. Temporal Response: All the mechanical schemes have poor temporal response as compared with all electronic ones.
4. **Presence or Absence of Mechanical Fatigue**: All the mechanical schemes have more or less the possibility of mechanical fatigue.

The two schemes which have been proposed very recently [30], [31] feature the low insertion loss, because both of these are all-fiber devices. In addition, the Faraday-rotator device features a relatively fast response, whereas the RFC device features the endlessness in control as seen in Table VI.

**VIII. Conclusions**

Recent advances in coherent optical fiber communication systems, in particular those in BER measurements and polarization-state stabilization techniques have been reviewed. Active research and development are still in progress; the state-of-the-art will again change drastically in coming few years. Probably the first application of the coherent optical fiber communications technology will be seen within several years, and it will become quite common in the next century. Meanwhile, a number of by-products of the research toward the coherent schemes will be put into practical use in conventional optical fiber communications.

At IOOC-ECOC ’85 at Venice, Italy, in October 1985, following the review talk upon which this paper is based, several papers were presented to report new experiments of coherent optical fiber communications [32]–[35]. Significant achievements were the transmission distance of 251 km at bit rate of 400 Mbit/s [33] and 150 km at 1 Gbit/s [34], and the achievement of bit-error rate of 10⁻⁹ with only 90 received photon/bit [34]. However, the details of these reports are omitted here and introduced elsewhere [36], together with discussion on technical limitations of the coherent schemes such as laser-noise problem.

**References**


References for Table I [PCM-ASK/BER Measurements]


References for Table II [FCM-FSK BER Measurements]


References for Table III [PCM-PSK BER Measurements]


[P5] Same as [P3].


[P7] Same as [P3].

References for Table IV [PCM-DPSK BER Measurements]


[D3] Same as [P3].


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