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# Coherent Optical Communications and Photonic Switching

edited by

G. Prati

# COHERENT OPTICAL COMMUNICATIONS AND PHOTONIC SWITCHING

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*edited by*

G. PRATI

Instituto di Scienze dell'Ingegneria
Università degli Studi de Parma
Parma, Italy



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# COHERENT OPTICAL COMMUNICATIONS AND PHOTONIC SWITCHING

# FOREWORD

These are very exciting times for those of us who work with coherent optical communications, photonic switching, and advanced photonic technologies in general. With the successful deployment of the first trans-oceanic fiber optic transmission systems, and the wide acceptance of fiber for telecommunications trunking applications, we can all look forward to what I believe is the ultimate challenge: bringing fiber to the end user - with the concurrent broadband services that fiber can support. This application will greatly increase the demands for transmission capacity and the need for advanced high-speed switching technologies. A challenge we face is in the use of advanced wavelength multiplexing technologies (like coherent communications) to make the delivery of broadband services to the end-user economical and flexible to implement. Another opportunity that lies within this context is the utilization of photonic technologies to facilitate the implementation of practical broadband switching and networking techniques. This includes both centralized switches at various types of communication network nodes, as well as various forms of distributed switching.

The use of coherent communications (or alternatively direct detection, dense wavelength multiplexing techniques) provides increased flexibility in the design of broadband distribution networks. The extraordinarily large bandwidth of fiber can be exploited without the need for electronics operating beyond the data rates associated with the user services. Thus, fiber can be shared conveniently amongst several or many users - an important factor in making fiber-to-the-customer cost effective. In addition, the passive nature of many components that can be used in wavelength multiplexed networks - e.g., splitters- is attractive when one considers the need to remotely locate multiplexing and branching points. The recent upsurge in interest, and the corresponding results, on optical amplifiers adds yet another dimension of flexibility and opportunity that is synergistic with coherent communications and other forms of dense wavelength multiplexing.

Thus, it is with great hopes and expectations that the community of researchers working on coherent communications techniques and applications moves forward into the next decade.

To capture the whole realm of possibilities for the utilization of photonic technologies within switching and networking applications we shall use the designation: photonic switching. However, as the later papers will explain, this does not imply the direct replacement of photonic devices into existing equipment and network architectures as a substitute for electronic devices.

Photonic switching will be used here to capture the general opportunity to utilize existing and new photonic devices in conjunction with existing and new electronic devices to realize new or improved switching and networking capabilities. It includes such things as simple mechanically activated optical switches used for network protection switching and network reconfiguration, where an entire optical signal is redirected as a unit. It includes the use of optical interconnections within equipment to facilitate internal high speed and high density interconnects. It includes the use of tunable transmitters and receivers at the core of a high speed packet or circuit switch, with large quantities of electronics providing supporting interface and control functions. In principle it includes the concept of an all-optical switch-whose architecture and component technologies have yet to be invented.

I am happy to say that in the past several years materials and device scientists have been coming together more and more with systems architects to uncover the real opportunity areas for coherent communications and photonic switching. In the early days of fiber optics (circa 1970) it was somewhat easier to visualize the application (e.g. the architecture) which represented the target for a practical realization of the technology. Basically, the target everyone was pursuing was a point-to-point fiber optic link with higher capacity, longer repeater spacing, and thus lower cost than 1.5-2 Mb/s digital transmission over copper wire pairs. One could calculate, relatively easily what the requirements were to break even against the incumbent technology. It is unlikely that coherent communications will be used only as another alternative for increasing the performance or reducing the cost of point-to-point links. It is unlikely that an all-optical switch will emerge which can be directly substituted for today's electronic switches - except perhaps in some relatively simple applications such as the protection switching application mentioned above. Therefore, one has to simultaneously consider new network applications, new network architectures, and a variety of hybrid photonic-electronic possibilities in order to uncover the applications likely to be most attractive.

It is my hope that this book will shed some light on the current thinking regarding where the applications are, what the technology status is, and where the opportunities are for future research.

Steward D. Personick

Network Technology Research
Bell Communications Research,Inc.
Red Bank, New Jersey USA

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# PART 1

# COHERENT OPTICAL COMMUNICATION TECHNIQUES AND TECHNOLOGIES

# Recent Status of Coherent Lightwave Technologies for High-Speed Long-Haul and FDM Transmission

Toshihiko SUGIE and Kiyoshi NOSU

NTT Transmission Systems Laboratories
Yokosuka-shi, Kanagawa, Japan

The recent progress of coherent lightwave technology is described. Emphasis is placed on experimental optical heterodyne / homodyne detection and optical FDM (frequency division multiplexing) techniques, including newly developed optical devices.

## I. Introduction

Coherent lightwave techniques, which make use of optical frequencies or phase, are having significant impact on communication systems. Because of the possibility of an improvement in receiver-sensitivity up to 20-30 dB, research and development activities have been accelerated. However, to realize coherent lightwave systems many technical difficulties have to be overcome ; such as frequency stabilization, laser-spectrum purification, insensitive polarization states of the fibers, and modulation/demodulation techniques. With the development of coherent light sources, sophisticated communication technologies that have very large bandwidth potential of the carriers will become feasible [1]~[3].

The present research trends of coherent lightwave transmission are summarized as follows ; (1) high-speed, (2) long-haul transmission, and (3) dense optical multiplexing. A key technology for high-speed and long-haul transmission is optical heterodyne/homodyne detection and that for dense optical multiplexing is optical FDM (frequency division multiplexing). This paper reviews the current state of coherent lightwave technology on these points.

## II. High-speed and Long-haul transmission

### II-1 Fundamental technique

Heterodyne/homodyne detection has a lot of advantagies. With FSK or PSK modulation, heterodyne detection permits significant improvement in receiver sensitivity, and it allows signal processing of the electrical intermediate frequency band, such as, equalization of optical signal waveform distortion which is caused by the fiber chromatic dispersion. These merits and applications of heterodyne/homodyne detection are summarized in Table I . A system configuration for heterodyne/homodyne detection is shown in Fig.1. Transmitter

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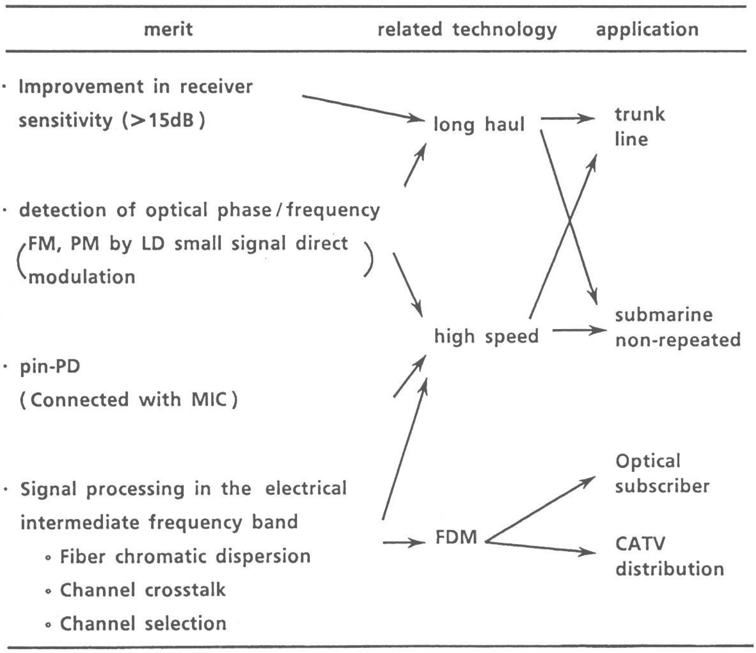
The authers are with NTT Transmission Systems Laboratories, 1-2356, Take, Yokosuka-shi, Kanagawa, 238-03, Japan.

Tel. +81 - 468 - 59 - 3041, Fax. +81 - 468 - 59 - 3396

**Table I Merits and applications of heterodyne / homodyne detection**




configurations are classified into direct modulation and modulation by an external modulator. Technical difficulties must be overcome to realize transmission systems, such as narrow linewidth [4][5] and frequency stabilization of laser diodes (LD), insensitivity to polarization states of the fibers [6] and modulation/demodulation techniques. These difficulties and the techniques recently proposed are summarized in Table II as well as the related experiments.

(1) Transmitter

A transmitter consists of an LD, a modulation circuit and a stabilization circuit. Both narrow LD linewidth and modulation characteristics are most important, because they determine a modulation format which can be applied.

(i) Linewidth : Narrow linewidth in LD must be realized to reduce the required IF bandwidth and excess penalty. Although required linewidth is determined by the modulation format, a linewidth less than 1 MHz must be achieved for several gigabit transmission, for example $10^{-3} \times$ bit rate for FSK-heterodyne differential detection. This has been resently achieved by long cavity DFB-LDs, MQW-DFB-LDs, and LDs with an external cavity, by several organizations.

(ii) Modulation technique : Frequency modulation (FM) is easily carried out by using LD frequency chirping that corresponds to the injection current. This means that CP-FSK is achieved by direct modulation of the LD injection current. However, an external modulator must be used for ASK and PSK. A wideband

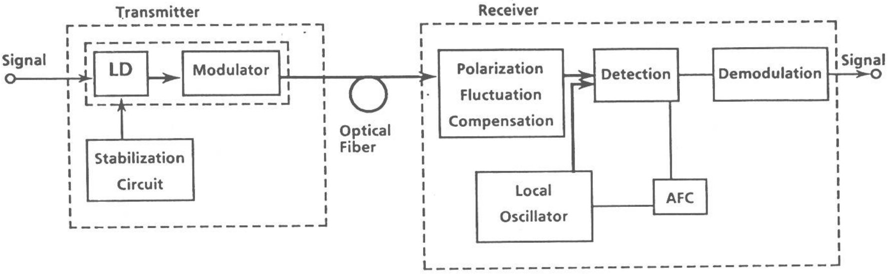



Fig 1. A system configuration for heterodyne/homodyne detection

## Table II Technical problems of high-speed, long-haul transmission

| Item | proposed technique | Feature | Reference |
|---|---|---|---|
| [Transmitter] narrow linewidth-LD | · Long cavity DFB-LD<br>· MQW-DFB-LD<br>· LD with external cavity | 760 KHz<br>700 KHz<br>70 KHz | (7), (8), (11)<br>(9)<br>(10) ··· |
| flat FM response | · Multielectrode-DFB-LD<br>· equalization<br>· cording | <br>~4 GHz<br>AMI,bipolon FSK | (7) (11)~(14)<br>(15) (16)<br>(17) |
| external modulator | · $LiNbo_3$-modulator<br>· MQW-modulator | 10 GHz<br>20 GHz | (18) (19)<br>(20) |
| [Optical fiber] polarization insensitivity | · polarization controller<br>· polarization diversity<br>(conventional two IF method<br>frequency conversion method)<br>· polarization-maintaining fiber<br>· polarization scrambling | fiber, $LiNbO_3$, YIG | (21)~(23)<br><br>(6), (24)<br>(25)<br>—<br>— |
| improvement of dispersion effect | · IF equalization | 202 km, 4 Gb/s, 8 Gb/s | (26) (27) |
| nonlinear effect | · SBS | less than +10 dBm | (28) |
| [receiver] preamplifier | · Inductor peaking<br>· twin-pin, HEMT(balanced receiver) | 2~8 GHz<br>8.7 pa/√Hz | (29)<br>(30) |
| IF amplifier | · HEMT (HIC)<br>· Inductor peaking | ~20 GHz<br>20 dB | (31) |
| frequency tracking | · differential detector with 90° hybrid | ±30 MHz (1.8 Gb/s) | (33) |
| phase diversity | · optical hybrid | | (32) |

frequency response is required in these devices. A flat FM response for an LD has been achieved for FSK transmission by using a multielectrode DFB-LD. Fig.2 shows typical configuration and characteristics for this multielectrode DFB-LD. Narrow linewidths of less than 1 MHz and with a flat FM response up to several GHz are achieved . Codes such as AMI and bipolar FSK have been proposed for direct modulation to avoid LD non-flat FM response effect. An equalization circuit for FM response is employed to drive the LD and this can improve the response by about 1~2 times as compared to an LD without equalization circuit.

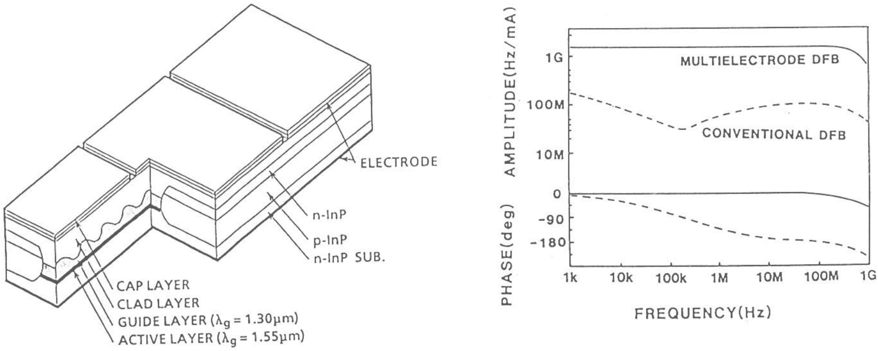
Wideband external modulators of more than 10 GHz have been developed for ASK, and PSK. These modulators were fabricated by $LiNbO_3$, and MQW. A low drive voltage (half wavelength) of less than 10 V and a low insertion loss of 3 dB are achieved by using the coplanar waveguide as a traveling-waveguide.

(2) Optical fiber

The polarization state fluctuation and chromatic dispersion of fibers attribute to the penalty increase in heterodyne/homodyne detections. A lot of techniques have been proposed to overcome these problems.

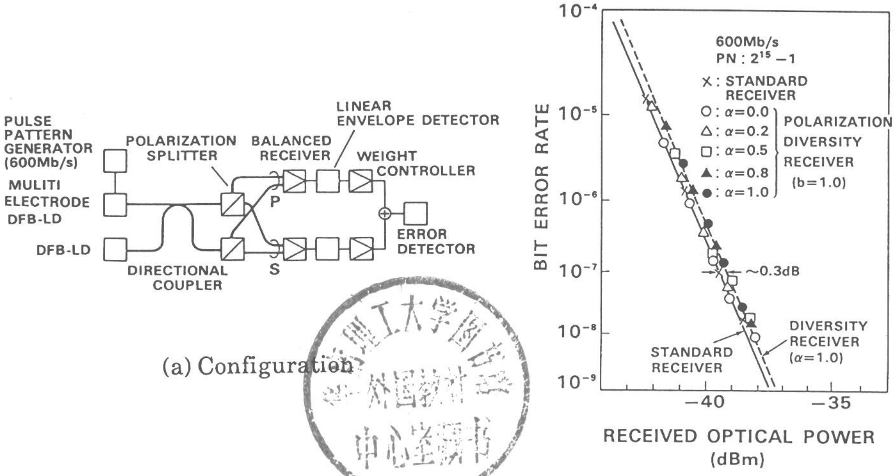
(i) Polarization insensitivity : The polarization state of the optical fiber fluctuates, when LD light injected into the fiber propagates. However, the polarization state of the LD signal propagated along an optical fiber must coincide with that of the local LD light. There are several typical methods; polarization-maintaining fiber, polarization controller, polarization diversity and polarization scrambling. In these technique, sensitivity degradation, response time and excess loss are important. These must be reduced to negligible. At present, various types of polarization controllers are proposed such as coiled fiber, opt-electric crystal, and Faraday rotator among others. Takeing account of response time, polarization diversity is most attractive because of stable operation that is independent of oplarization fluctuation, although the two orthogonal polarization components are separately detected, A polarization diversity experiment is shown in Fig.3 [24]. Degradation due to polarization fluctuation is estimated to be less than 0.3 dB for this diversity technique. Recently, a polarization diversity optical receiver that uses polarization frequency conversion technique with two local oscillators has been proposed [25].

(ii) Dispersion : Fiber dispersion attributes to distortion of the waveform transmitted along a long fiber. Although degradation by fiber dispersion




(a) Structure (b) FM response

Fig 2. Multielectrode DFB-LD




(a) Configuration

(b) Bit error rate performance

Fig 3. Polarization diversity



depends on the modulation/demodulation format, waveform distortion is compensated for by IF equalization in heterodyne detection, i.e. signal processing in the IF band. A 202 km long fiber transmission experiment is demonstrated at 4 and 8 Gb/s using a microstrip line delay equalizer [26] [27]. Frequencies for signal and local oscillator LDs are allocated by the delay characteristics of the transmission fiber and the IF equalization circuit.

(iii) Non-linear effect : Among the non-linear effects in a fiber, transmitted power that is limited by stimulated Brillouin scattering (SBS) is considered to be problem to long haul transmissions. Although several experiments and theoretical considerations have been carried out from the viewpoints of modulation format, and modulation speed [28], this fatal effect on long haul transmissions can not be reported on at present. This is becoming a serious problem as higher optical power is being injected into fibers.

(3) Receiver

(i) Optical receiver and IF amplifier : A heterodyne/homodyne receiver consists of pin-photo diodes, low noise amplifiers, a local oscillator and a frequency/phase tracking circuit. A lot of effort has been made to achieve both wide bandwidth and low noise characteristics for each component and the receiver configuration. A balanced receiver that consists of dual pin-PDs is proposed to suppress local LD relative intensity noise (RIN) by more than 10 dB. IF HIC amplifiers employing HEMT have also been developed with a averaged Noise Figure of 4.1 dB in the range of from 100 MHz to 18 GHz [31]. These two opints are inevitable to achieve long haul transmission [29].

(ii) Phase diversity : As bit rate increases, the required bandwidth of the IF amplifier, instead of LD linewidth, increases in the heterodyne detection. Although homodyne detection has advantages for the required amplifier bandwidth and detection sensitivity, optical PLL must be developed. Experiments have been carried out but problems still remain to be solved. However, phase diversity is a promising technique to overcome these problems for