UNIVERSITI PUTRA MALAYSIA

OPTICAL BEAT INTERFERENCE IN OPTICAL COMMUNICATION SYSTEM

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FK 2006 17

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

February 2006

To my parents

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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February 2006

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Subcarrier Multiplexing (SCM) can be used to increase the capacity of any optical network. Both Single-Optical-Carrier (SOC) and Multiple-Optical-Carrier (MOC) SCM systems can be employed. However, in SCM-MOC systems, when two lasers carrying subcarrier channels operate with very close spaced wavelength, beating between the lasers and beating between the lasers and Four-Wave Mixing (FWM) terms can occur. This will increase the noise at the photodetector. This type of noise is called Optical Beat Interference (OBI) and it is dependent on the accumulated Chromatic Dispersion (CD) experienced in the transmission. This thesis establishes a new approach to reduce OBI by suppressing the optical carrier. The effect of OBI in the presence of FWM is also examined and analyzed. Additionally, applications of OBI in optical communications are investigated, particularly for measuring CD and the modulator frequency chirp.

The new approach for OBI reduction uses optical carrier suppression. This method achieved a 28 dB improvement in the Carrier-To-Interference (CIR) ratio. In addition, OBI penalty in SCM-MOC network in the presence of FWM is studied mathematically and verified through a simulation exercise, which shows that the maximum number of subcarrier or the bandwidth of the SCM-MOC system will be limited by Main-Beating and FWM-Beating when FWM is present.

The novel technique for CD measurement is performed by simultaneously launching a pump and probe optical signals at ω_1 angular optical frequency separation, and two phase-conjugated terms into the SMF. The relative power of the beat frequencies that appear after the photodetector at ω_1 and at $2\omega_1$ is used to determine the accumulated CD. This technique was successfully demonstrated using a Semiconductor Optical Amplifier (SOA) as a phase conjugator to achieve a 19 dB relative power variation as a result of up to 1900 ps/nm CD change.

A new method to measure the modulator frequency chirp parameter using OBI is performed in two steps. In the first step, the frequency separation between two optical signals passing through a phase conjugator is changed, produces a resonance reference frequency as a result of the accumulated fiber CD. In the second step, an RF modulated signal passes through the same length of fiber as in the first step. A second resonance frequency is produced as a result of fiber CD and modulator chirp. The difference between the two resonance frequencies is used to measure the modulator chirp. The new method achieves a measurement range of ± 5 and maximum resonant frequency of 8.1 GHz at an accumulated CD 1632 ps/nm.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra
Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

GANGGUAN PUKULAN OPTIK DALAM SISTEM KOMUNIKASI OPTIK

Oleh

MALIK TAYSIR AL-QDAH

Februari 2006

Pengerusi: **Profesor Madya Mohamad Khazani Abdullah, PhD**

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Penggabungan Sub-Pembawa boleh digunakan untuk meningkatkan keupayaan sistem komunikasi optikal. Kedua-dua sistem Penggabungan Sub-Pembawa dengan Pembawa Optikal Tunggal ataupun Pembawa Optikal Pelbagai boleh digunakan untuk tujuan ini. Walaubagaimanapun, di dalam sistem Pembawa Optikal Pelbagai, apabila dua laser yang diolah dengan saluran sub-pembawa beroperasi dalam jarak gelombang yang terlalu hampir, fenomena pukulan diantara dua laser dan diantara kedua-dua laser dan komponen Campuran Empat Gelombang akan berlaku. Keadaan ini akan meningkatkan kebisingan di pengesan foto. Jenis kebisingan ini dikenali sebagai Gangguan Pukulan Optik dan ianya bergantung kepada Pertebaran Kromatik terkumpul semasa penghantaran. Thesis ini memperkenalkan cara untuk mengurangkan Gangguan Pukulan Optik dengan kaedah Pengurangan Pembawa Optik. Kesan Gangguan Pukulan Optik yang digabungkan dengan kesan Campuran Empat Gelombang juga turut dikaji. Selain dari itu, kajian juga dibuat tentang penggunaan Gangguan Pukulan Optik di dalam sistem komunikasi optikal, khususnya untuk mengukur Pertebaran Kromatik dan Perubahan Frekuensi di dalam pengolah optik.

Kaedah baru untuk mengurangkan Gangguan Pukulan Optikal adalah dengan mengurangkan kuasa pembawa optik. Kaedah ini berjaya memperbaiki Nisbah Pembawa kepada Gangguan dengan kadar 28 dB. Kesan Gangguan Pukulan Optik yang digabungkan dengan kesan Campuran Empat Gelombang diselidik dengan kaedah matematik dan disahkan melalui simulasi. Keputusan menunjukkan bilangan saluran sub-pembawa akan dihadkan oleh kehadiran Gangguan Pukulan Optikal dan Campuran Empat Gelombang.

Kaedah baru untuk mengukur Pertebaran Kromatik adalah dengan menghantar dua gelombang, gelombang pam dan gelombang pengesan dengan perbezaan jarak frekuensi optikal ω_1 dan dua lagi gelombang yang dibalikkan fasanya ke dalam SMF. Kuasa relatif kedua-dua jenis pukulan selepas pengesan foto pada frekuensi ω_1 dan $2\omega_1$ digunakan untuk mengukur Pertebaran Kromatik terkumpul. Kaedah ini berjaya dibuktikan dengan penggunaan Penguat Optikal Semikonduktor sebagai pembalik fasa. Variasi kuasa relatif yang berjaya diukur adalah sebanyak 20 dB dengan perubahan Pertebaran Kromatik terkumpul sehingga 1900 ps/nm.

Kaedah baru untuk mengukur Perubahan Frekuensi di dalam pengolah optik dengan menggunakan Gangguan Pukulan Optik dibuat dalam dua fasa. Dalam fasa yang pertama, jarak perbezaan frekuensi optik di antara dua gelombang optik yang melalui pembalik fasa ditukar. Ini akan menghasilkan frekuensi resonans rujukan hasil daripada Pertebaran Kromatik terkumpul. Dalam fasa yang kedua, satu gelombang optikal yang diolah oleh satu gelombang frekuensi radio dihantar melalui gentian optik yang sama. Ini akan menghasilkan frekuensi resonans hasil daripada Pertebaran Kromatik terkumpul dan Perubahan Frekuensi di dalam pengolah optikal. Perbezaan diantara kedua-dua frekuensi resonans ini boleh digunakan untuk mengukur Perubahan Frekuensi di dalam pengolah optik. Kaedah baru ini mampu mengukur Perubahan Frekuensi dengan julat ukuran sebanyak ± 5 dan hanya menggunakan frekuensi pengolahan 8.1 GHz dengan pertebaran kromatik terkumpul 1632 ps/ nm.

ACKNOWLEDGEMENTS

I would like to thank my God for shedding on me health and keeping my brain working to the extent of completing this research, which I hope will contribute to the welfare of mankind.

I would like to express my most sincere appreciation to my supervisor Associate Professor Dr. Mohamad Khazani Abdullah for his valuable attention, guidance, and support throughout my Ph.D. program. I would like to also thank other members of my committee, Professor Dr. Burhanuddin and Associate Professor Dr. Kaharudin Dimyati for their assistance. I would like to thank Mr. Hairul Azhar for the valuable discussion throughout my research.

I gratefully acknowledge members of photonic group, past and present, who helped me make my PhD pursuit enjoyable and rewarding. Finally I would like to convey my appreciation to my parents, wife, brothers and sisters for their support over the course of this thesis.

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LIST OF ABBREVIATIONS

ASE	Amplified spontaneous emission
BER	Bit-error rate
BPF	Band Pass filter
BPSK	Binary phase shift keying
CATV	Cable television
CD	Chromatic dispersion
CIR	Carrier to interference
CW	Continuous wave
DC	Direct current
DFB	Distributed feedback laser
DMUX	Demultiplexer
DRA	Distributed Raman amplifier
DWDM	Dense wavelength division multiplexing
DFF	Dispersion flatened fiber
DSF	Dispersion shifted finer
EDFA	Erbium-doped fiber amplifier
ESA	Electrical spectrum analyzer
FWM	Four wave mixing
FWM-OBI	Four wave mixing-optical beat interference
IMD	Inter-modulation distortion
ISI	Inter-symbol interference
LASER	Light amplification by stimulated emission of radiation

LED	Light emitting diode
LP	Low pass filter
MUX	Multiplexer
OBI	Optical beat interference
OSA	Optical spectrum analyzer
PMD	Polarization mode dispersion
PSD	Power spectral density
PSK	Phase shift keying
SCM	Subcarrier Multiplexing
SCM-MOC	Multiple optical carrier SCM
SCM-SOC	Single optical carrier SCM
SBS	Stimulated Brillouin scattering
SRS	Stimulated Raman scattering
SDM	Space division multiplexing
SOA	Semiconductor optical amplifier
SMF	Single mode fiber
SSMF	Standard single mode fiber
SNR	Signal to noise ratio
SPM	Self phase modulation
TBF	Tunable band pass filter
TLS	Tunable laser source
TDM	Time division multiplexing
XPM	Cross phase modulation

WDM	Wavelength division multiplexing

CHAPTER 1

INTRODUCTION

1.1 Introduction

Optical fiber communications has been growing rapidly over the past years. The major break-through in optical fiber transmission came after invention of Erbium-Doped Fiber Amplifier (EDFA) and Distributed Raman amplifier (DRA). Due to the wide gain bandwidth of the EDFA and DRA, the Wavelength-Division Multiplexing (WDM) channels can be simultaneously amplified and transmitted over long distances. The bit rates have reached 1.28-Tbit/s over 70 km for single-channel [1], and 3-Tbit/s (300 x 11.6-Gbit/s, C+L band) over 7,380 km, 1.28-Tbit/s (32 x 40-Gbit/s, C band) over 4500 km, 1.52-Tbit/s (38 x 40-Gbit/s, C band) over 6200 km, 10.2-Tbit/s (256 x 42.7-Gbit/s, C+L band) over 300 km, and 10.92-Tbit/s (273 x 40-Gbit/s S+C+L band) over 117 km for WDM systems [2-6]. The spectral efficiency has reached 1.6 (bits/s)/Hz [7].

In order to maximize the information transfer over any communication link, it is common to multiplex several signals onto the transmission medium. There are essentially four multiplexing approaches to increase transmission capacity on a fiber-optic link. The Space Division

Multiplexing (SDM) approach keeps the same bit rate and uses more fiber utilizing one wavelength to increase network capacity [8]. It is the most straightforward method. However, this approach requires more fibers, which may require laying new fiber, which could be very expensive and also requires separate set of repeaters for each fiber. Therefore, this approach is only used when distance is short enough not to use any repeaters and fibers are largely available. The Time Division Multiplexing (TDM) approach increases the transmission bit rate on the fiber using one wavelength [9]. This approach requires high bit rate transmission on the fiber, which will be limited by dispersions such as Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD). This approach is also limited by the electronic interface speed. The WDM approach keeps the same bit rate and uses more wavelengths to increase network capacity over the same fiber [10]. This approach can be designed to be transparent which will allow different bit rate and protocol to be carried by different wavelengths. However, this approach requires separate terminating equipment for each wavelength - laser and detector.

Another technology that can be used to increase the efficiency of bandwidth utilization is the Sub-Carrier Multiplexing (SCM). It is an old technology that has been studied and applied extensively in microwave and wireless communication systems. A combination of SCM and WDM (by using multiple optical carriers) has the potential for achieving a bandwidth in excess of 1 THz. Since the signal is transmitted optically, the microwave carrier acts as a subcarrier for the optical carrier, and the technique is referred to as SCM.

1.2 Multi-wavelength SCM Optical System

In SCM, the transmitted signal is generated in two stages. First, several microwave subcarriers are modulated by the data. Second, the resulting microwave signals modulate the optical carrier [11]. SCM has been a well known and an attractive technique for voice, data, and video distribution in the multi-access lightwave systems, especially, cable-television (CATV) applications [12, 13]. SCM can take advantage of well-developed existing electronic technologies, including analog and digital modulation as well as microwave and baseband signaling. There is also no need for synchronization between each channel and a master clock, as is the case for TDM systems. It also takes advantage of the full bandwidth capacity of Single Mode Fiber (SMF) and electro-optic components. Because individual channels in SCM are independent, SCM systems have great flexibility in allocation of bandwidth, and can thus readily accommodate rapidly evolving changes. In addition to being flexible, SCM systems are also cost effective, as they provide a way to take advantage of the bandwidth potential of fiber optics using conventional well-established microwave components.

In SCM, all microwave subcarriers can modulate one optical carrier [14], or each one of them can modulate a separate optical carrier [15]. SCM with a single optical carrier (SCM-SOC) is illustrated in Figure 1.1, while SCM with multiple optical carriers (SCM-MOC) is illustrated in Figure 1.2. Optical carriers in an SCM-MOC configuration have the same average center frequency.

In SCM-MOC system, different lasers operating at different wavelengths (nominally with the same wavelength) will produce beat interference at the photodetectors, causing outage of the microwave subcarriers [16], which modulate the optical carriers. This subcarrier outage will severely degrade the performance of SCM system. This phenomenon is called Optical Beating Interference (OBI) and it is the highlighted issue in this thesis.

OBI is a limiting factor for SCM networks [17]. It is a result of two or more users transmitting simultaneously on the nominally same optical channel by using different subcarrier frequencies. Since the optical carrier frequencies are usually slightly different due to environmental changes, their optical mixing would produce beating terms in the