Implementing Subcarrier-Based Control in Optical Networking

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***Abstract* — Optical subcarriers can be used for several different important applications in optical networks. This paper will explore the implementation of optical subcarriers for control, monitoring, routing, and transmission in networks. Additionally, we will discuss the limitations imposed on subcarriers by the optical fiber itself, such as RF fading caused by chromatic dispersion and polarization-mode dispersion.**

I. Introduction

For many applications, it is quite advantageous to transmit several analog or digital subcarrier-multiplexed (SCM) RF channels over an optical fiber link or network. These applications include: cable TV, wireless network interfaces, microwave photonic systems, and control information for optical networking and optical packet switching [1-4]. For example, SCM header transmission can be processed at a rate much lower than the data packet bit-rate.Moreover, subcarrier modulation is important for data grooming, bandwidth allocation flexibility, and access networks.

In this paper, we will discuss a diverse set of topics, including the implementation of optical subcarriers for control, monitoring, and routing in networks. Additionally, we will discuss the RF-power-fading limitations placed on SCM systems that are caused by optical-fiber-based chromatic dispersion and polarization-mode dispersion.

II. All-Optical Wavelength Shifting of Subcarrier Channels

It may be critical for future networks to provide wavelength shifting of subcarrier modulation to ensure high-throughput performance. Wavelength shifting is important because it enables wavelength reuse, contention resolution and efficient use of wavelength domain. Difference frequency generation (DFG) achieves memoryless, linear, transparent wavelength shifting with extremely low crosstalk and quantum limited additive noise in a large wavelength range.

We demonstrated all-optical wavelength shifting of subcarrier channels in a periodically poled lithium niobate (PPLN) structure, which uses a $\chi^{(2)}:\chi^{(2)}$ process for 1.5-µm pumping [5]. The pump (λ_{pump}) creates a second harmonic at $\lambda_{pump}/2$, which interacts with λ_{signal} to form a wavelength shifted copy at ~($2\lambda_{pump}-\lambda_{signal}$). DFG is an instantaneous process with a high operation bandwidth in excess of several THz and has similar up- and down-conversion efficiencies. Moreover, wavelength conversion efficiency of DFG is not proportional to signal power, thereby creating linear transfer characteristics in a large dynamic range (see Fig. 1 and 2) [6].

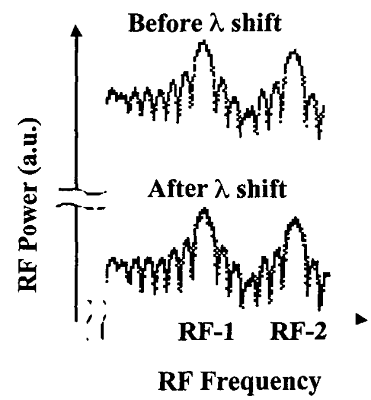

Fig. 1.RF spectra before and after the wavelength shift.

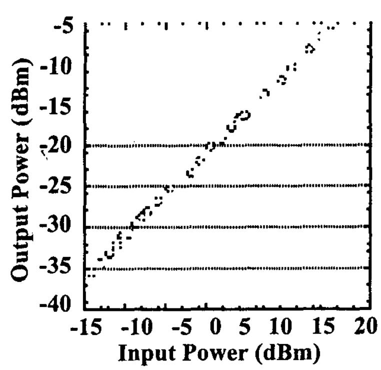

Fig. 2.Linearity of DFG: wavelength shifted signal power vs. signal power, measured after the PPLN.

II. TUNABLE RF-POWER-FADING COMPENSATION OF MULTI-CHANNEL DOUBLE-SIDEBAND SCM

Transmitting traditional double-sideband (DSB) subcarrier-multiplexed signals over a fiber is problematic due to the fiber's chromatic dispersion. Data recovery for double-sideband transmission requires that the two sidebands arrive at the receiver simultaneously. Unfortunately, the frequency-dependent fiber dispersion produces a deleterious time delay between the transmitted sidebands, thereby causing serious RF power fading that is a function of subcarrier frequency, fiber distance, and accumulated dispersion [7]. Several methods have been previously reported for circumventing the problem of chromatic-dispersion-induced power fading [8,9]. However, in future reconfigurable optical networks, the transmission distance could change dramatically, potentially necessitating tunability. Additionally, it would be advantageous to compensate the accumulated dispersion for several SCM channels simultaneously.

We reported the use of a nonlinearly-chirped FBG to compensate tunably for dispersion-induced RF power degradation in multiple-channel SCM transmission links and reconfigurable networks. This grating has the ability to uniquely provide a tunable dispersion to incoming signals since the time delay as a function of wavelength for the FBG follows a nonlinear shape. The exact dispersion induced by the grating for a given wavelength can be tuned by mechanically stretching the FBG [10]. We demonstrated tunable compensation of RF power fading for two SCM/BPSK 156-Mbit/s channels in which the fading is simultaneously reduced from 15 and 6 dB, respectively, to <0.5 dB for each channel (see Fig. 3) [11].

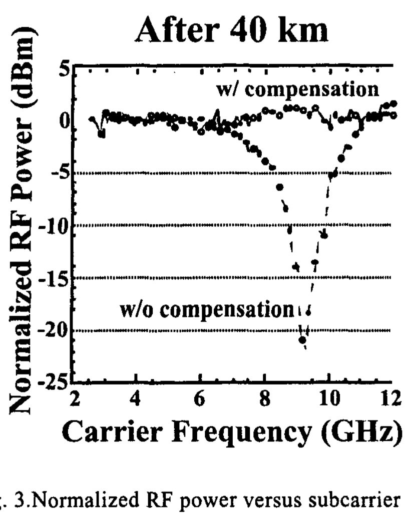

Fig. 3.Normalized RF power versus subcarrier frequencies with and without compensation for 40-km SMF transmission.

II. PMD-INDUCED POWER FADING FOR DOUBLE- AND SINGLE-SIDEBAND MICROWAVE SIGNALS

Polarization mode dispersion (PMD) is one of the critical challenges in next-generation microwave and millimeter-wave fiber-links since a severe power fading penalty results in a potential loss of the recovered signal. The cause for PMD is the unintentional circular asymmetry of optical fiber due to noncircular waveguide geometry or asymmetrical stress around the fiber core. In an ideal symmetrical fiber, the state of polarization (SOP) of an optical wave can be represented as the superposition of two indistinguishable orthogonally-polarized modes with the same propagation constants. However, the loss of circular symmetry in real fibers gives rise to two distinct orthogonally-polarized modes with different propagation constants causing a difference in the group velocities [12]. This differential group velocity can be described by the differential group delay (DGD), i. e. first-order PMD, between the two orthogonal principal-states-of-polarization (PSP's) of the fiber. Due to random variations in the perturbations along the fiber span the average DGD accumulates in a random fashion with a Maxwellian probability distribution [13-15]. Furthermore, the perturbations vary over time due to environmental changes. PMD causes a negative effect in system performance by inducing a stochastic and dynamically-changing degradation of high-speed digital baseband data channels. Moreover, transmission of analog and digital subcarrier-multiplexed (SCM) signals over fiber will also be severely affected by PMD.

The DGD between the fast and slow PSP of an optical sideband in a SCM signal causes a phase difference in the corresponding received subcarrier signals in the photodetector, as shown in Fig.1. Superposition of the photo-currents may lead to serious power fading of the recovered subcarrier signal due to destructive interference that is a function of subcarrier frequency, accumulated DGD, and optical power splitting ratio between the PSP's [16]. The PMD-induced fading penalty in a microwave fiber-link is essentially dependent on the subcarrier frequency (>> GHz), which can be similar to the bit rates of high speed optical baseband transmission systems, and not the data rate of the SCM signal itself (< Gbit/s). Such an optical link may accumulate PMD values of ~10 ps over a 100 km distance leading to a significant fading penalty for the transmitted millimeter-wave signals. Furthermore, higher-order PMD, such as polarization-dependent chromatic dispersion and depolarization effects, can cause additional distortion and degradation of the transmitted signal.

We investigated the statistics of PMD-induced power fading as a function of DGD for DSB-SCM and SSB-SCM signals using a realistic PMD source. We found that both DSB and SSB intensity modulated subcarrier signals exhibit stochastic system performance in the presence of PMD (see Fig. 4) [17].

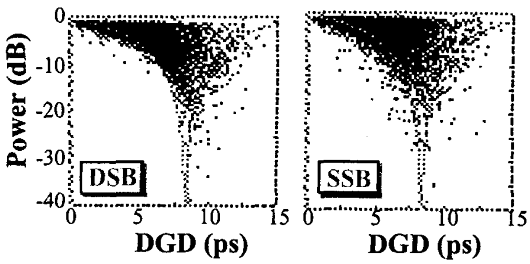

Fig. 4.Received subcarrier power vs. DGD for 10,000 independent polarization samples using DSB and SSB intensity modulated subcarrier signal.

II. SIMULTANEOUS PMD MONITORING OF SEVERAL WDM CHANNELS USING SUBCARRIER TONES

Polarization mode dispersion (PMD) has emerged as a critical hurdle for next-generation high bit rate digital transmission systems (≥10 Gbit/s/channel). Since the birefringence of a fiber changes randomly along a fiber link, PMD effects are stochastic and time varying. Moreover, since PMD decorrelates the states-of-polarization (SOPs) of different WDM channels, each wavelength-division-multiplexed channel experiences different amounts of PMD at any given time.

We reported a simple technique for simultaneous and independent PMD monitoring of WDM channels in 10 Gbit/s systems. A subcarrier tone is added to each of the WDM channels using a 10% modulation depth (power penalty <0.3 dB) [18]. The subcarriers have the same power but slightly different frequencies. We show through statistical measurements that the subcarrier power fading due to PMD is strongly correlated to the PMD-induced degradation on that channel. In our demonstration we use a single module to monitor the PMD of two channels by tracking each channel's subcarrier tone power (see Fig. 5). This technique does not require any optical demultiplexing of the WDM channels.

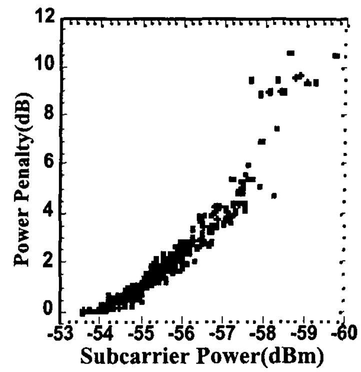

Fig. 5.Power penalty as a function of subcarrier tone power.

II. DISPERSION DIVISION MULTIPLEXING FOR DOUBLING THE SPECTRAL EFFICIENCY OF SCM

Future applications of SCM may be limited by the inherent spectral inefficiency of this technique. In conventional double sideband intensity modulation for subcarrier multiplexed signals, propagation along a fiber results in a time delay between the lower and upper sidebands due to chromatic dispersion. This deleterious time delay causes serious RF power fading that is a function of subcarrier frequency, fiber distance, and accumulated dispersion.

We demonstrated a novel technique for transmitting two different SCM data streams on the same wavelength and at the same subcarrier frequency by taking advantage of chromatic dispersion-induced power fading. This novel technique for combining the two data streams and improving the overall spectral efficiency is accomplished by fading, or "shadowing," one subcarrier channel after modulation onto the optical carrier. This is achieved by applying a certain amount of dispersion to the "shadowed" channel before combining it with the normal, or "non-shadowed," subcarrier channel for transmission. At the receiver, standard detection will produce the "non-shadow" subcarrier channel, since the "shadow" channel will be faded. To recover the shadow channel at the receiver, we apply the same amount of dispersion that was applied at the transmitter side for the "shadowing" process. The "shadow" channel is now recovered, whereas the "non-shadow" channel is faded (see Fig. 6) [19].

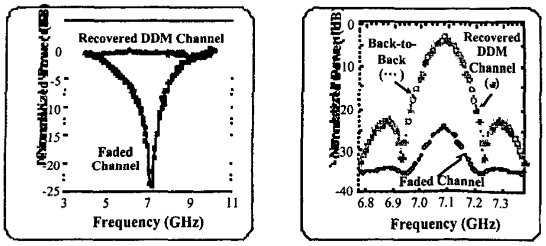

Fig. 6. (a) Normalized frequency response plots of the faded and recovered signals. (b) Electrical power spectrums for the back-to-back, faded, and recovered subcarriers are plotted.

II. DDM FOR IN-BAND SUBCARRIER-HEADER-BASED PACKET SWITCHING

Packet-switched all-optical networks need to process the header to efficiently route packets to the appropriate destination [1]. Subcarrier-multiplexed transmission of the header enables rapid and on-the-fly processing. Yet a major disadvantage in the standard SCM header transmission is that the subcarrier frequency is typically much higher than the data bit rate.

We demonstrated a method to transmit an SCM header at a subcarrier frequency lower than the data-rate, specifically at 7.7 GHz for 10 Gb/s data-rate, using dispersion division multiplexing (see Fig. 7) [20]. This is not possible using standard SCM transmission, since the subcarrier placed at such a low frequency can't be filtered out efficiently and this would deteriorate the detected data performance greatly. This technique permits efficient optical bandwidth utilization and results in little power penalty for the received data, since the SCM header channel is invisible with respect to the data channel detector. Moreover, there is no need for modifying the data receiver architecture.

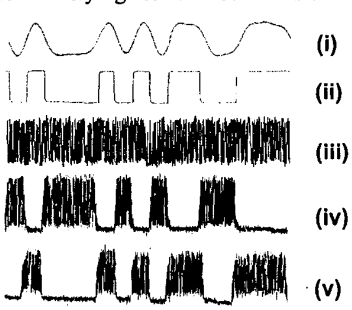

Fig. 7. (i) Recovered SCM header, (ii) output of the threshold detector, (iii) 10 Gb/s data stream before the switch, (iv) output of the switch port 0, (v) output of the switch port 1.

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