Reductions of Multiple-Access Interference in Fiber-Grating-Based Optical CDMA Network

Jen-Fa Huang and Chao-Chin Yang

Abstract—A fiber Bragg grating (FBG) encoder/decoder scheme based on correlation subtractions of nearly orthogonal M-sequence codes is presented. With proper coder design, a receiver can reject interfering users and obtain quasi-orthogonality between optical code-division multiple-access (CDMA) users in the network. However, optical CDMA networks may be degraded by multiple-access interference (MAI) due to nonflattened incoherent sources and nonideal FBG coders. A compensating module is therefore proposed to compensate for such MAI effects. As a result, the MAI effects induced by nonideal FBG coders can be perfectly eliminated by the compensating module. With spectral width reduction on the incoherent source, the scheme can partly compensate the MAI effects induced by nonflattened sources and further reduce the average error probability in the system performance.

Index Terms—Fiber Bragg grating (FBG), multiple-access interference (MAI), optical code-division multiple access (OCDMA), pseudo-orthogonal codes.

I. INTRODUCTION

In today’s optical communications, fiber capacity has to keep pace with rapid traffic increases due to continuing growth in the use of phones, multimedia, and computer networks. Wavelength-division multiple-access is a promising solution for increasing the transmission capacity on optical communication links. Motivated by the successful capacity improvement of code-division multiple-access (CDMA) techniques in wireless communications, many people have become interested in the development of optical CDMA systems.

One of the earliest examples of optical CDMA is the use of optical delay lines and optical orthogonal codes for CDMA time-domain coding [1]. The apparatus is typically used for time delays or for pulse repetition rate multiplication. Many papers have also discussed the use of broadband short pulses [2] or broadband continuous-wave sources [3] on confocal lenses to accomplish frequency-encoded CDMA. This scheme is more commonly used for pulse shaping, since phases can be directly manipulated. Unfortunately, the tapped-delay line or the confocal-lenses scheme suffers from high splitting or insertion losses due to the optical-fiber-based coding system.

Fiber Bragg gratings (FBGs) [4] are more convenient for inscribing the spectral codes necessary for fiber-optic CDMA applications. It has been shown that cascaded fiber gratings can provide time-resolved changes in the wavelength domain. Griffin et al. [2] used coherence coding in a multiple Bragg grating array to implement optical frequency-hopping CDMA. Chen et al. [5] investigated ultrashort-pulse propagation in fiber Bragg gratings with wavelength-division multiplexing (WDM) and CDMA applications. The generation of ultrafast trains of short optical pulses is of considerable interest for coherent photonic CDMA with fiber grating encoders/decoders. Grunnet-Jepsen et al. [6] incorporated phase shifts and wavelength chirps among the grating segments and demonstrated coherent spectral phase coding of pulses for use in CDMA systems.

Previously, Pfeiffer et al. [7] proposed a spectral-coding scheme by employing Fabry–Pérot filters at the transmitters to encode the periodically sliced LED spectra and utilizing a branching device at the receivers to distribute optical/electrical (O/E)-converted signals to different filters to retrieve the desired data. Alternately, Huang and Hsu [8], [9] proposed an FBG-based optical CDMA scheme in which the gratings spectrally encode light signals from electrical/optical (E/O)-modulated LEDs at the transmitters, and decorrelate the summed spectral chips with balanced photodiodes at the receivers. We see that the two approaches are both based on spectral orthogonality coding and differential detection, but the basic coding mechanisms are quite different. Even more, the proposed mechanism based on FBG filters in this study is much easier.

We configured the FBG decoder on the basis of correlation subtractions of pseudo-orthogonal codes to overcome the limiting factor of multiple-access interference (MAI) on the system performance of the fiber-optic CDMA network. Maximal-length sequence (M-sequence) codes were used to exemplify the coding and correlation processes among fiber-optic CDMA users. By assigning the $N$ cycle shifts of an M-sequence codeword to $N$ users, we achieve an optical CDMA network that can theoretically support $N$ simultaneous users. The capacity of the optical CDMA network is dependent upon the ability of the decoder to cancel MAI, which increases with the number of users in the system.

An optical CDMA system can be further degraded by MAI due to nonflattened incoherent sources and nonideal FBG filters. The purpose of this paper is to construct an FBG-based incoherent amplitude encoding system of spectrally sliced incoherent sources and experimentally demonstrate that this scheme is feasible. In view of the spectral leakage problem due to nonideal factors, a compensating module is proposed to compensate for such leakage-induced MAI. With the compensating module, the system consists of, at most, $N = 1$ transmitter and receiver pairs connected in a star configuration. One specific user channel unmatched to all of the other users is used to collect MAI effects caused by the nonideal grating transfer functions.

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The remainder of this paper is organized as follows. In Section II, a fiber-optic CDMA network scheme based on FBGs is presented. The coding devices are prewritten with well-designed optical CDMA address codes. Section III describes an experimental setup to validate the spectrally pseudo-orthogonal FBG-based fiber-optic CDMA network. Section IV presents a compensating module to compensate for MAI effects. The MAI-compensation processes for overcoming the nonideal FBG filtering effects are clarified. Section V evaluates the general system performance in terms of signal-to-interference ratio (SIR). Concluding remarks are given in Section VI.

II. FBG-BASED OPTICAL CDMA (OCDMA)

The discussed fiber-optic CDMA network is based on the spectral coding of incoherent broadband optical sources via FBGs. In such incoherent OCDMA system, the chip delay time caused by fiber gratings is far less than the optical chip duration and has a minor effect on networking performance. Incoherent broadband lightwave sources include those of edge-emitting LEDs, super-luminescent diodes (SLD) and erbium-amplified spontaneous emissions (Er-ASE). These sources offer broadband spectrum, high emitting power, and low cost due to high yields in packaging technology.

FBGs can be used to implement various forms of optical CDMA, including frequency hopping [2], [6], direct sequence [7]–[9], code recognition [10], two-dimensional wavelength/time spreading [11], [12], and amplitude and/or phase spectral coding [13], etc. For the two-dimensional OCDMA coders, the arrayed waveguide gratings (AWGs) approach [14], [15] can be used to achieve the same functionality as FBG-based systems.

Fig. 1 shows the FBG-based incoherent broadband fiber-optic CDMA encoder and decoder proposed by Huang and Hsu [8]. At the transmitting end, Fig. 1(a), the encoder consists of a series of FBGs, an intensity modulator, and an incoherent broadband optical source. At the receiving end, Fig. 1(b), the decoder is comprised of a matched series of FBGs, a balanced photodetector, and an information-decision device. We call the decoder and encoder “matched” if the series of decoder gratings are the same as the encoder gratings, but with a time-reversed order for grating path alignment purposes. It means, for the synchronous correlation subtraction to occur at the differential detectors, the optical path length in the reflecting branch is required to be identically equal to that in the transmitting branch (or within some path tolerance). The decoder gratings in a time-reversed order relative to the encoder gratings will compensate for the optical path delay and make every wavelength chip arrive at the photodiodes in nearly the same time interval.

In the FBG encoder shown in Fig. 1(a), incoherent broadband LED source is modulated with user’s data bits using amplitude shift keying (ASK) [also known as on-off keying (OOK)]. In such scheme, the transmitted bit “1” refers to light passing and the bit “0” refers to light blocked. The fiber grating coder is tuned to various designed center wavelengths using specified code sequences. When the encoded broadband signal is sent to the decoder, Fig. 1(b), the wavelengths satisfying the Bragg condition are reflected. It can be said that the broadband modulated signal is being “sliced”.

With a properly written optical CDMA coding pattern, the reflected light field from the FBGs will be spectrally encoded onto an address code denoted by the code vector $\mathbf{X}_k = (X_{k0}, X_{k1}, \ldots, X_{kN-1})$ or $\mathbf{X}_k(\lambda) = \sum_{n=0}^{N-1} p_n(\lambda - n\Lambda_c)X_{kmn}$. Here, $X_{kmn} \in \{0,1\}$, for $0 \leq n \leq N-1$, is the $n$th chip value of the $k$th user’s spectral code. $N$ is the periodic length of the address code (or the number of chips per bit). $\Lambda_c$ is the pulse width and $p_n(\lambda)$ is the fundamental pulse of each chip in the spectral domain. By fundamental pulse, we mean the spectral response with unity energy for an ideal FBG filter tuned to Bragg wavelength. This ideal output resembles the classic rectangular or square wave. Any filter with a nonsquare spectral response is a nonideal filter. This paper assumes a Gaussian distribution for each fundamental chip pulse. Approximately equivalent pulse energy for each spectral chip is also assumed.

Each transmitter broadcasts its spectrum-encoded signal to all of the receivers in the network. The received signal spectrum is a sum of all of the active users’ transmitted signal spectra $\mathbf{Z}(\lambda) = \sum_{k=1}^{N} b_k \mathbf{X}_k(\lambda - I_k)$, where $b_k$ is the $k$th user’s information bit, and $I_k$ is the $k$th user’s arbitrary spectral shift. The receiver applies a correlating decoder to the incoming signal to extract the desired bit stream. The correlator output for the $k$th user is

$$\hat{X}_k = \int_{-\infty}^{\infty} X_k(\lambda)Z(\lambda)d\lambda = b_k \int_{-\infty}^{\infty} [X_k(\lambda)]^2d\lambda + \sum_{j \neq k} b_j \int_{-\infty}^{\infty} X_k(\lambda)X_j(\lambda)d\lambda.$$

(1)
where \( W \) is the bandwidth corresponding to the spectral code length. The first term is the desired data stream for the \( k \)th user. The second term is the MAI coming from the other users.

Quasi-orthogonal codes having good correlation properties (i.e., high autocorrelation peaks with low sidelobes and low cross-correlation functions) are needed to reduce undesired interference from other simultaneous users. Such MAI is the dominant factor investigated in this paper that limits the performance of optical CDMA communications. To reduce the undesirable effects caused by MAI, a matched FBG encoder/decoder pair is configured based on the orthogonal correlation functions of the nearly orthogonal M-sequence codes.

The shift-and-add property of the M-sequence code says that for sequences \( (X) = (x_0, x_1, \ldots, x_{N-1}) \) and \( (Y) = (y_0, y_1, \ldots, y_{N-1}) \) to be in the same set of M-sequence codes, the relation \( (Y) = (T^n X) \) must be satisfied, where \( T \) is a recurrence-shift operator. For example, \( (Y) \) is \( (T^n X) = (x_{N-n}, x_0, \ldots, x_{N-2}) \) for \( n = 1 \), or \( (Y) \) is \( (T^2 X) = (x_{N-2}, x_{N-1}, x_0, \ldots, x_{N-3}) \) for \( n = 2 \). An M-sequence code of length \( N \) can therefore provide for \( N \) different users through \( N \) cycles shifting of a codeword. By applying the above properties, the correlation between code sequences \( (X) \) and \( (Y) \) can be retrieved as

\[
R_{XY}(n) = \sum_{i=0}^{N-1} X_i Y_{i+n} = \begin{cases} \frac{(N+1)}{2}, & \text{for } n = 0 \\ \frac{(N+1)}{4}, & \text{for } n = 1 \text{ to } N-1. \end{cases}
\]

Note that, for \( n = 0 \), \( X \) and \( Y \) are the same code vector, and \( R_{XY}(n) \) corresponds to the autocorrelation of \( X \) (or \( Y \)). For \( n = 1 \) to \( N-1 \), \( X \) and \( Y \) are different code vectors, and \( R_{XY}(n) \) corresponds to the cross correlation between \( X \) and \( Y \).

In the proposed network system, the light source is directly modulated by the data flow in the transmitter and then encoded using the FBG coder to achieve frequency encoding. Different cyclic shifts of a set of M-sequences are assigned for different FBG coders, so all users’ data can transmit in the same fiber channel. In the receiver, through an optical circulator, the received signal is divided into complementary transmitting and reflecting branches of spectral chips. These two branches of spectral signals are sent to a balanced detector that computes the correlation difference, \( R_{XY}(n) - R_{X \bar{Y}}(n) \), resulting in

\[
R_{XY}(n) - R_{X \bar{Y}}(n) = 2R_{XY}(0) - \frac{N+1}{2},
\]

for matched codes pair;

\[
= \frac{2(N+1)}{4} - \frac{(N+1)}{2} = 0,
\]

for unmatched codes.

From (3), it is obvious that only the original data is obtained when the encoder and decoder are a matched pair. The receiver rejects the signal coming from an interfering user with the sequence \( (Y) = (T^n X) \) for \( n \neq 0 \). By assigning \( N \) cycle shifts of an M-sequence codeword to \( N \) subscribers, an optical CDMA network is designed that can support \( N \) simultaneous users without any interference. Complete orthogonality between the fiber-optic CDMA users is, therefore, achieved theoretically.

III. EXPERIMENTAL SETUP FOR VALIDATION

To verify the idea presented in this paper, a code length for \( N = 3 \) is designed and tested. The possible central wavelengths of the FBG coders are designated as the code vector \( (\lambda_1, \lambda_2, \lambda_3) \), with wavelength vector element \( \lambda_i \) being either “present” (logic “1”) or “absent” (logic “0”). For a network user assigned the signature \((1, 0, 1)\), the FBG coder has cascaded gratings with central wavelengths of \( \lambda_1 \) and \( \lambda_3 \). For a network user with the signature \((0, 1, 1)\), the central wavelengths are \( \lambda_2 \) and \( \lambda_3 \).

In the experimental setup shown in Fig. 2, a broadband LED or Er-ASE source is modulated using a data sequence \((1, 0, 1, 0, 1, 0, \ldots \text{in our experiment})\) and then sent to the grating encoder. The spectral chip wavelengths are \( \lambda_1 = 1536 \) nm, \( \lambda_2 = 1543 \) nm, and \( \lambda_3 = 1550 \) nm, all the lengths of the FBGs are around 1 cm, and the reflectivities of the FBGs are 99.8%. The spacing between the FBGs is around 5 cm in the encoder/decoder structure. Note that this configuration requires the optical path length of the reflecting and transmitting branches be exactly equal in each decoder. Also note that a reflecting signal chip passes through the coupler two times while the transmitting signal chip passes the coupler one time. The additional pass through the coupler makes the reflecting signal power 3 dB less than the transmitting signal.

In the matched case, the signature sequence is \((1, 0, 1)\) in both the FBG encoder and decoder. That is, the FBG encoder and decoder are the cascaded \( \lambda_1 = 1536 \) nm and \( \lambda_3 = 1550 \) nm gratings. After decoding, the wavelength chips \( \lambda_1 \) and \( \lambda_3 \) are retrieved in the reflecting branch, and no wavelength chips are in the transmitting branch. For the sake of simplicity, the data rate in the experiments is performed at 10 kHz in this fetal stage of demonstration.

Fig. 3(a) shows the measured spectrum and the photodetected voltage function for the reflecting branch. The reflecting signal passes through the \( 2 \times 2 \) coupler twice, and the measured peak
voltage is 189 mV at the photodetector output. The measured spectrum and the corresponding voltage function for the transmitting branch are shown in Fig. 3(b). The measured peak voltage is 37 mV for the transmitting branch. Note that the signal output at the transmitting branch is not perfectly zero, which is an energy-leakage problem due to nonideal spectral filtering of the grating coder.

In the unmatched case, the signature sequences are respectively (1, 0, 1) and (0, 1, 1) in the FBG encoder and decoder. That is, the FBG encoder is the cascaded $\lambda_1 = 1536$ nm and $\lambda_3 = 1550$ nm gratings, and the FBG decoder is the cascaded $\lambda_2 = 1543$ nm and $\lambda_3 = 1550$ nm gratings. As expected, wavelength $\lambda_3$ is retrieved in the reflecting branch and wavelength $\lambda_1$ is retrieved in the transmitting branch.

Fig. 4(a) shows the measured spectrum and the photodetected voltage (43 mV) for the reflecting branch. The measured spectrum and the corresponding voltage (171 mV) for the transmitting branch are shown in Fig. 4(b). Note that, due to passing through the coupler twice, the reflected signal suffers an additional 3-dB loss compared to the transmitted one, and the electrical signal will be 6 dB lower. A factor of four-times difference in the detected signals is, therefore, obtained, whereas the reflected signal only suffered a factor of two additional losses.

Certain factors that affect the experimental results exist in the fiber-optic CDMA network. First, as shown in Figs. 3(a) and 4(a), the reflected signal chips suffer from an additional 3-dB loss on passing through the coupler twice. This factor can be overcome using a circulator instead of a 3-dB coupler in practical application. Second, as shown in Figs. 3(b) and 4(b), the matched signal output chips at the transmitting branch are not perfectly zero. This is attributed to the nonideal spectral filtering of the grating coder. Furthermore, the nonflattened light source may also cause signal power fluctuations across the power spectrum and result in MAI.

The nonideal factors such as the extra coupler loss in the reflecting path and the nonsquare grating filter are obvious in the experimental validation. In general, a 1-dB variation across the data-bit spectrum would cause each channel to leak by as much as 20% into the orthogonal receivers. This level of MAI would severely limit the total number of channels that can be multiplexed. As compared to theoretical predictions, MAI effects from nonideal FBG filters and nonflattened lightwave sources exist in practical fiber-optic CDMA networks. A compensating module is proposed to reduce the MAI effects induced by nonideal factors.

IV. MAI COMPENSATING SCHEME

In the FBG-based optical CDMA network discussed so far, we have assumed the system to be ideal in that every spectral chip is perfectly 1-unit or 0-unit energy. Under these conditions, the system is confirmed to be an ideal fiber-optic CDMA by the correlation subtraction of (3). However, practical nonideal light sources and fiber gratings can induce MAI.

Analysis of the discussed fiber-optic CDMA network can be accomplished by treating the light sources and the fiber gratings as spectral functions. The spectrum-transfer function of a broadband light source is designated $S(\lambda)$. The reflected spectrum-transfer functions of the FBG encoder and decoder are designated by $G_e(\lambda)$ and $G_d(\lambda)$, respectively. For simplicity, we
assume the response of the photodiode be constant in the spectral domain. Following this approach, the intensity functions at the two photodiodes of the balanced detector can be found as

\[ I_R = \eta_R \cdot \int_{-\infty}^{\infty} S(\lambda) G_e(\lambda) G_d(\lambda) d\lambda \] (4)

\[ I_T = \eta_T \cdot \int_{-\infty}^{\infty} S(\lambda) G_e(\lambda)(1 - G_d(\lambda)) d\lambda \] (5)

where \( \eta_R \) is the optical loss in the reflecting branch of the receiver and \( \eta_T \) is the optical loss in the transmitting branch of the receiver. In other words, they are the ratio of the photodetector input power to the light-source power under the condition of perfect correlation.

In a practical network, the interfering signals \( I_R \) and \( I_T \) derived from (4) and (5) cannot be perfectly cancelled on the balanced photodetectors. Nonideal fiber gratings and nonflattened light sources both cause nonzero MAI values. Since the incoherent LED or Er-ASE spectrum is not uniform, the reflected spectral chips from FBGs have different amplitudes. The different amplitudes of the chips could affect the orthogonality of the code family. One way to counter this effect would be to simply reduce the width of the total frequency band of the spectral code, and then encode the data light field in the center of the source spectrum, where it is flatter. Unfortunately, even flattened, real sources have variations across the power spectrum that will spoil the cancellation of the two partial integrals of the spectral chips on the balanced photodiodes, thus creating MAI.

In order to manage the MAI problems caused by the nonideal grating filters, an MAI-compensating scheme for the FBG-based optical CDMA network is proposed as shown in Fig. 5. The system consists of, at most, \( N \) transmitter and receiver pairs connected in a star configuration. One user channel is lost in the system. This user channel is used for MAI compensation. Only through matched signature address codes can the transmitted optical sequence be extracted successfully on the receiver decoder. The task of the receiver is to extract the desired user’s bit stream from the received signal, which consists of the desired data stream and the undesired MAI.

In Fig. 5, to eliminate MAI effects, a compensating decoder (the Decoder \#N) is reserved that is unmatched to all of the other coders. The purpose of this specific decoder is to collect the MAI effects caused by the nonideal grating transfer functions. In the following, we consider the case in which the light source is perfectly flattened (that is, \( S(\lambda) = 1 \) in the spectrum coding area 1525–1575 nm, and the only nonideal factor is the grating transfer function. For the sake of simplicity, the reflected spectrum transfer functions \( G_e(\lambda) \) and \( G_d(\lambda) \) in the FBG encoder and decoder devices are modeled as Gaussian profiles

\[ G_e(\lambda) = \sum_{\epsilon=0}^{N-1} p_e \exp\left[\frac{-(\lambda - (\lambda_B + \epsilon \Delta \lambda_B))^2}{\sigma_B^2}\right] \] (6)

\[ G_d(\lambda) = \sum_{\delta=0}^{N-1} p_d \exp\left[\frac{-(\lambda - (\lambda_B + \delta \Delta \lambda_B))^2}{\sigma_B^2}\right] \] (7)

where \( \lambda_B \) is the starting wavelength of the designed spectral chips (1525 nm), \( \Delta \lambda_B \) is the chip spacing (8.33 nm for \( N = 7 \)), \( \sigma_B \) is the spectral width of the grating (0.15 nm), and \( p_e \) and \( p_d \) are M-sequence code sets for the FBG encoder and decoder, with subscripts \( e \) and \( d \) being variable numbers regarding the code sets. It is found that the simple expressions in (6) and (7) can be obtained if the FBG filter is simulated as a Gaussian function, and it will be much easier to characterize the intensities from the balanced detectors.

If the light source spectrum is flattened, we expect that the transmitted power, due to the fiber grating Gaussian profile, is the same for different users. Deduced from the intensity functions of (4) and (5), we denote \( I_R \) and \( I_T \) as intensity parameters in the reflecting and transmitting branches after the decoding processes for the matched code pairs in the transmitter and receiver. Parameter \( I_T \) can be visualized as spectral leakage due to nonideal grating filters. For the unmatched code pairs, by taking optical losses \( \eta_R = \eta_T \) in (4) and (5), the received power can
be assumed 0.5I_R in the reflecting branch, and 0.5I_R + I_T in the transmitting branch.

MAI effects exist in the FBG-based optical CDMA network for both the matched and unmatched encoder/decoder addresses. Let us assume that the system has N address codes and the jth address code is assigned to the compensator. The power in the reflecting and the transmitting branches of the compensating decoder can be written as

\[ P_{RN} = \sum_{i=1}^{N} b_i I_i(0.5I_R) \]
\[ P_{TN} = \sum_{i=1}^{N} b_i I_i(0.5I_R + I_T) \]

where \( b_i \) is the data bit, and \( I_i \) represents the light source intensities for the \( i \)th active user. The compensating signal can therefore be represented as

\[ P_c = |P_{RN} - P_{TN}| = \sum_{i=1}^{N} b_i |I_i(I_T)|. \]  

For an intended decoder with a signature code matched to that of user \( k \), the power intensities in the reflecting and the transmitting branches is

\[ P_{Rk} = b_k I_k I_R + \sum_{i=1, i \neq k}^{N} b_i I_i(0.5I_R) \]
\[ P_{Tk} = b_k I_k I_T + \sum_{i=1, i \neq k}^{N} b_i I_i(0.5I_R + I_T). \]

Thus, the \( k \)th decoder output after MAI compensation can be represented as

\[ P_k = |P_{Rk} - P_{Tk}| - P_c = b_k I_k I_R. \]

For the other active users, with the corresponding FBG decoder matched to the intended signature code, the compensated decoder output can be similarly obtained. It is easy to confirm that the decoded output is zero for the other unmatched decoders corresponding to those inactive users. The MAI effect due to the Gaussian profile in the FBG coders is, therefore, perfectly eliminated.

V. SYSTEM PERFORMANCE EVALUATION

The compensating module can completely eliminate the MAI effects induced by the nonideal FBG coders. However, the MAI effects caused by nonflattened sources cannot be eliminated completely in the compensating module. We will, therefore, evaluate the system performance of the OCDMA in the general cases of nonflattened sources and compensated FBG coders.

Assume that the incoherent LED lightwave signal has a Gaussian profile in the spectral coding area (1525–1575 nm)

\[ S(\lambda) = \frac{1}{\sqrt{\pi \sigma_l}} \exp \left[ -\frac{(\lambda - \lambda_l)^2}{\sigma_l^2} \right] \]  

where \( \lambda_l \) (\( \approx 1550 \) nm) is the center wavelength of the LED-like source, and \( \sigma_l \) (\( \approx 53 \) nm) is the bandwidth of the adopted source. In this case, the MAI effect cannot be eliminated because the frequency chip allocation for a user’s signature code is different from other users. In other words, the number of MAI terms depends on the code distribution we choose in our compensation network scheme.

Upon incidence of broadband lightwave signal \( S(\lambda) \) on an FBG coder, the nonideal spectral shape \( s_i \) of the reflected chips through the fiber gratings can be assumed to be Gaussian. For an M-sequence code \( (x_0, x_1, \ldots, x_{N-1}) \) of length \( N \), with spectral energy \( s_i \) for the reflected chips and \( b_k \) the spectral shape of the transmitted chips through the FBGs, the SIR can be represented [3] as

\[ \text{SIR} = \frac{\left( \sum_{k=1}^{N} (I_{Rk}^2 - I_{Tk}^2) \right)^2}{\sum_{k=1}^{K} (I_{Rk}^2 - I_{Tk}^2)^2}. \]  

The numerator is the desired optical signal power in a bit period, and the denominator is the MAI power from \( K - 1 \) interfering users with \( K \) as the number of active users. By employing the expression \( \text{BER} = \text{erfc}(\sqrt{\text{SIR}/2})/2 \), we can estimate the possible number of active users under a specified bit-error rate (BER).

In (13), the signal term \( \sum_{i=0}^{N-1} x_i^2 s_i^2 \) accounts for the fact that the signal at the positive photodiode undergoes two reflections from the FBGs (once in the encoder, and once in the decoder). Similar deductions are for the two terms in the interference. The terms \( I_{Rk}^2 = \sum_{i=0}^{N-1} x_i^2 x_{i+k} s_i^2 \) and \( I_{Tk}^2 = \sum_{i=0}^{N-1} x_i^2 x_{i+k} s_i s_{i+k} \) represent the mean intensities received on the positively and negatively biased photodiodes, respectively, for interfering user \( k \). Using Gaussian statistics for the decision variable resulting from the integration of the balanced photodetectors output, the subtraction \( I_{Rk}^2 - I_{Tk}^2 \) would be zero in the case of a perfect cancellation of the interfering signals.

In the MAI term \( I_{Rk}^2 - I_{Tk}^2 \) in (13) for interfering user \( k \), we see that the mean intensity functions \( I_{Rk}^2 \) and \( I_{Tk}^2 \) are dependent on the code distribution. Different code sequences have different code distributions and hence, different coded amplitudes of spectral chips. It is easy to understand that if we collect the MAI using a specified decoder (the compensation decoder \( N \) in Fig. 5), and then subtract the MAI sum from the intended decoder, the effect of the MAI is largely eliminated. The best choice for the signature sequence assigned for the compensating module (the decoder \( N \)) has to be neither concentrated nor dispersed in the code distribution. If the decoder sequence is more concentrated than the compensation code sequence, the MAI sum from the various users is a positive value. On the contrary, if the decoder sequence is more dispersed than the compensation code sequence, the MAI sum is a negative value.

Since user power at the balanced photodiodes is different with different numbers of active users, it is hard to predict the MAI value in normal operation conditions where the number of users fluctuates over time. Moreover, due to nonflattened optical spectra of incoherent LED or Er-ASE sources, the reflected spectral chips from FBGs will have different amplitudes. These
To eliminate MAI effects, a decoder unmatched to all of the other coders was reserved as a compensating module. This compensating module can completely eliminate the MAI effects induced by the nonideal FBG coders. On the other hand, because the optical spectrum of the incoherent source is not flat, the spectral flatness relied on the position chips take along the spectrum will not be perfect. The MAI caused by nonflattened light sources is a positive or negative value if the decoder signature is more concentrated or dispersed than the compensating code. This MAI could be partly compensated for by reducing the spectral width toward the center of the spectrum, where it is flatter. The coded spectral chips then will have more flattened amplitudes.

In conclusion, with the proposed MAI-compensating OCDMA encoder/decoder scheme, this paper allows every user to successfully receive information data bits delivered from the transmitter. The compensating module is capable of eliminating the MAI effects caused by nonideal FBG coders.

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REFERENCES


VI. CONCLUSION

A simple experiment was performed to demonstrate the effects of nonideal light sources and spectral filters for an FBG-based optical CDMA network. It was concluded that the discussed fiber-optic CDMA system possesses two inherent nonideal factors affecting MAIs. The first factor relates to the nonideal spectral shape of the FBG, which increases the measured power value in the transmitting end. The second factor involves the nonflattened spectral shape of the light source. Because of this nonflattened light spectrum, the energy of the spectral coding chips is not equal. Consequently, MAI problems are produced because users with different code sequences occupy different distributions in the wavelength domain.


Jen-Fa Huang received the M.A.Sc. and Ph.D. degrees from the Department of Electrical Engineering at the University of Ottawa, ON, Canada, in 1981 and 1985, respectively. Since 1991, he has been with the Department of Electrical Engineering at the National Cheng Kung University, Taiwan, where he is currently an Associate Professor. Previous to 1991, he was with MPB Technologies, Montreal, PQ, Canada, in the Optical Communication Laboratories working on the TAT-9 transatlantic undersea lightwave transmission project. His research interests are mainly in the areas of optical communications, all-optical data networking, and fiber-optic sensors.

Chao-Chin Yang was born in Tainan, Taiwan, in December 1972. He received the B.S. degree from the Department of Electrical Communications at the National Chiao Tung University, Taiwan, in 1996. Since 1999, he has been a graduate student in the Department of Electrical Engineering, National Cheng Kung University, Taiwan, where he is currently working toward the Ph.D. degree in the area of optical fiber networks/communications. His major interests are in optical chaotic signal processing, multiuser optical communications, and in the DWDM data communication network.