Optical Code-Division Multiple Access Using Broad-Band Parametrically Generated Light

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***Abstract*—A novel approach for an optical direct-sequence spread spectrum is presented. It is based on the complementary processes of broad-band parametric down-conversion and up-conversion. With parametric down-conversion, a narrow-band continuous-wave (CW) optical field is transformed into two CW broad-band white-noise fields that are complex conjugates of each other. These noise fields are exploited as the key and conjugate key in optical direct-sequence spread spectrum. The inverse process of parametric up-conversion is then used for multiplying the key by the conjugate key at the receiver in order to extract the transmitted data. A complete scheme for optical code-division multiple access (OCDMA) based on this approach is presented. The salient feature of the approach presented in this paper is that an ideal white-noise key is automatically generated, leading to high-capacity versatile code-division multiple-access configurations.**

***Index Terms*—Code-division multiple access (CDMA), optical spread spectrum, parametric down-conversion, parametric up-conversion.**

I. Introduction

CODE-DIVISION multiple access (CDMA) is a well-known scheme for multiplexing communication channels that is based on the method of direct-sequence spread spectrum [1]. In CDMA, every channel is identified by a unique pseudonoise key, whose bandwidth is much larger than that of the input data. Ideally, the key should mimic the correlation properties of white noise and should be as long as possible in order to minimize the interference noise introduced by other channels; thus, a great deal of effort is invested in finding practical keys with good autocorrelation and cross-correlation properties [1].

The essential difference between CDMA and other multiplexing methods, such as time-division multiple access (TDMA) and frequency-division multiple access (FDMA), is that in CDMA, the resource allocated per channel is power, as opposed to time or bandwidth. This difference leads to three major advantages of CDMA compared with traditional multiplexing methods. First, CDMA is inherently flexible to dynamic changes in the bit rate and the quality of service [signal-to-noise ratio (SNR)] of any channel without affecting the total amount of data transmitted by all channels. If a channel is allowed to transmit more power, it can either improve the SNR or increase the bit rate of that channel. Consequently, this shared resource (power) can be dynamically allocated between the channels, and any channel can dynamically trade bit rate for signal to noise, and vice versa, at a given power. Second, CDMA is well adapted to dynamic changes of the number of simultaneously operating channels. Specifically, when one channel becomes inactive, the other channels benefit from the fact that the noise level is reduced. Thus, an allocated channel in CDMA that is not transmitting at a given time, *automatically* "frees its space" to other channels that need the bandwidth at that time, whereas in conventional methods, a costly system for dynamic allocation and compression is required in order to exploit inactive channels. Third, in CDMA all channels are equivalent, whereby the quality of service is that of the average channel, while in conventional methods, the quality of service is dictated by the worst channel. These advantages are eventually translated to an improved usage of the spectrum resource and a higher capacity for CDMA in many configurations.

It is obvious that the CDMA approach would be most attractive if it could be implemented optically. Indeed, several attempts have been made to incorporate optical CDMA (OCDMA) into optical communication networks [2]–[14]. The major obstacle is how to generate the direct-sequence key at the transmitter in order to encode the data and how to multiply the output of the receiver by the conjugate key in order to retrieve the data. Since, in current optical networks, the single-channel data rate is already close to the limit that electronic modulators and detectors can support and since the bandwidth of the key must be significantly broader than that of the data, it is impractical to generate the key and multiply by the conjugate key electronically. Thus, it is imperative to find a way to perform these operations *optically*.

This paper explains how to exploit the optical nonlinear process of parametric down-conversion in order to generate both an *ideal* key and its conjugate key, specifically, to develop a source that generates simultaneously both a broad-band white noise and its complex conjugate. Note that it is not necessary for CDMA that the key be previously known. Indeed, as long as both the key and the conjugate key are generated together, one can transmit the conjugate key along with the data to the receiver (at the cost of half the bandwidth). Then, the process of parametric up-conversion (also known as sum-frequency generation) is exploited to optically multiply the key and its conjugate key at the receiver. The processes of parametric down-conversion and up-conversion occur in any medium

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with second-order ($\chi^{(2)}$) nonlinearity. A common family of such media is that of nonlinear crystals, for example, BaB_2O_4 (BBO), $LiNbO_3$ (LN), $KTiOPO_4$ (KTP).

II. Parametric Conversion Processes

Parametric conversion processes were widely investigated over the last 35 years in both the classical and quantum mechanical frameworks [18]–[28]. Indeed, many devices based on these processes were developed, such as optical parametric oscillators (OPOs) and optical parametric amplifiers (OPAs).

The parametric down-conversion and up-conversion processes are depicted schematically in Fig. 1. Fig. 1(a) shows the parametric down-conversion, where energy is transferred from a high-frequency field (the pump field with frequency ω_p and wave vector $\vec{k}_p$) via the mediation of a nonlinear crystal to two lower frequency fields (the signal and idler fields at frequencies ω_s and ω_i and wave vectors $\vec{k}_s$ and $\vec{k}_i$, respectively). When the nonlinear medium is thick, this conversion occurs only if the phase-matching requirements are met. Specifically, $\omega_p = \omega_s + \omega_i$ and $\vec{k}_p = \vec{k}_s + \vec{k}_i$, i.e., both energy and momentum are conserved. In this down-conversion process, the phase of the generated signal field with respect to the pump is undefined *a priori* but will be opposite to that of the corresponding idler frequency ($\phi_i = \phi_p - \phi_s$), i.e., the signal and idler amplitudes are complex conjugates (see proof in Appendix I). Note that for a given pump frequency, there may be a broad band of signal–idler frequency pairs that fulfill the phase-matching requirement, depending on the specific dispersion characteristics of the nonlinear medium and on its thickness. The phase-matching bandwidth can reach hundreds of nanometers in the near infrared for thick crystals of up to several centimeters (as elaborated in Appendix II).

The process of parametric up-conversion is schematically depicted in Fig. 1(b). It is symmetrically inverse to the process of parametric down-conversion. Specifically, the energy is transferred from two low-frequency fields to a field at a high frequency that is equal to the sum of the two low frequencies. If this process is phase-matched, the phase of the generated field at the sum frequency is equal to the sum of the phases of the two low-frequency fields. Mathematically, this is equivalent to the statement that the complex field amplitude at the sum frequency is proportional to the *multiplication* of the complex amplitudes at the two low-frequency fields.

We note that although $\chi^{(2)}$ effects seem to be most practical for our purpose, other physical processes can also serve as the underlying mechanisms for the optical direct sequence communication scheme proposed here. In Appendix III, we generalize the discussion also to other processes, such as higher order nonlinear processes.

III. The OCDMA Scheme

A. Generation of the Direct-Sequence Key

The core of our approach for optical generation of the key lies in the special phase and amplitude relations between the optical fields that participate in the process of parametric down-conversion. Specifically, if a parametric source is broadly phase-matched and oscillates over a large bandwidth, there is no phase relation between the different signal (or idler) frequencies, so the signal (or idler) field is just a broad-band continuous-wave (CW) white noise, but since the phase of every signal frequency is opposite to that of the twin idler frequency, the signal and idler are *complex conjugates*. That is exactly what is required for the generation of an *ideal* key. To date, all other methods use complicated algorithms to predesign practical keys that approximate the characteristics of the desired ideal white-noise key [15]–[17]. These approximations are usually constrained by other design considerations, such as, the tradeoff between key length and design simplicity, yielding a nonoptimal result. In our approach, an ideal key is automatically generated via the physical process.

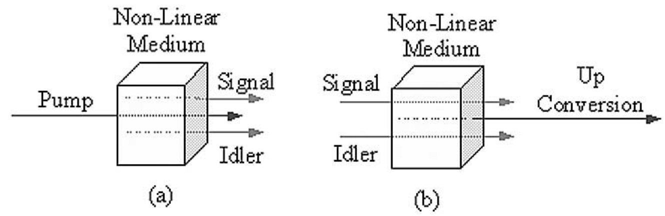

Fig. 1. Parametric processes of second-order nonlinearity. (a) Illustration of parametric down-conversion. (b) Illustration of parametric up-conversion (sum-frequency generation).

Now, the key can be externally modulated (multiplied) by the information, and both the modulated key (signal) and the conjugate key (idler) can be sent to the receiver end. Alternatively, one can modulate the narrow-band pump instead of the broad-band signal.

B. Multiplication by the Conjugate Key at the Receiver

In order to perform the multiplication by the conjugate key at the receiver, we exploit the process of parametric up-conversion. As long as the up-conversion efficiency is low, the intensity of up-converted light at frequency ω (denoted $R(\omega)$) is given by

$$R(\omega) \propto \left| \int d\omega' A(\omega') A(\omega - \omega') \right|^2 \quad (1)$$

where $A(\omega)$ is the slow-varying amplitude of the field at frequency ω. In (1), all the pairs of spectral amplitudes at frequencies that sum up to the frequency ω are added coherently. Obviously, a spectrally incoherent broad-band source yields very poor conversion efficiency, since the phases of spectral components are random, so the different pairs interfere almost destructively.

We now want to consider the up-conversion of light that was originally generated by parametric down-conversion. Since the signal and idler are complex conjugates, we can write

$$A(\omega) = A_s(\omega) + A_i(\omega) = A_s(\omega) + A_s^*(\omega_p - \omega) \quad (2)$$

where $A_s(\omega)$, the spectral amplitude of the signal field, has a random spectral phase. Assuming the spectral phases of the entire spectrum have been modulated by some general phase function $\phi(\omega)$, we obtain

$$A(\omega) = e^{i\phi(\omega)} \left[A_s(\omega) + A_s^*(\omega_p - \omega) \right]. \quad (3)$$

Inserting (3) into (1) yields

$$R(\omega) \propto \left| \int_0^{\frac{\omega_p}{2}} d\omega' \begin{bmatrix} A_s(\omega')A_s^*(\omega_p-\omega+\omega')+ \\ A_s^*(\omega_p-\omega')A_s(\omega-\omega')+ \\ A_s(\omega')A_s(\omega-\omega')+ \\ A_s^*(\omega_p-\omega')A_s^*(\omega_p-\omega+\omega') \end{bmatrix} \times e^{i\phi(\omega')+i\phi(\omega-\omega')} \right|^2. \quad (4)$$

Equation (4) contains four terms in the integrand. Since the phase of $A_s(\omega)$ is assumed to be random, integration of the last two terms will result in a negligible contribution to $R(\omega)$ because of destructive interferences. Yet, the first two terms are basically the spectral autocorrelation of the signal field, so they have a sharp peak at $\omega = \omega_p$. The peak value is

$$R(\omega_p) \propto \left| \int_0^{\frac{\omega_p}{2}} d\omega' \left|A_s(\omega')\right|^2 e^{i\phi(\omega')+i\phi(\omega_p-\omega')} \right|^2. \quad (5)$$

The result of (5) is equal to that obtained when up-converting an ultrashort transform-limited pulse, where the phase of all frequencies is known to be zero, after applying coherent pulse shaping to it [29], [30]. Thus, we establish equivalence between the down-converted light and coherent ultrashort pulses, although the down-converted light is neither coherent nor pulsed [31].

It is clear that the up-conversion peak intensity at the original pump frequency is dramatically enhanced compared with that obtained with incoherent white noise, since all the frequency pairs that sum up to the pump frequency add *coherently*. Since the coherent integral scales linearly with the ratio of the signal bandwidth to the pump bandwidth and the incoherent integral scales only as the square root of that ratio (random walk), the enhancement G in the up-conversion intensity is given by

$$G = \frac{R(\omega_p)}{R(\omega \neq \omega_p)} = \left| \sqrt{\frac{\Delta}{2\delta}} \right|^2 = \frac{\Delta}{2\delta} \quad (6)$$

where Δ is the total bandwidth of the down-converted light (signal and idler) and δ is the pump bandwidth.

In order to be able to fully utilize the enhancement in the up-conversion intensity, it is necessary to detect the up-conversion only within the pump bandwidth, filtering out the broad incoherent up-conversion spectrum. Here, the fact that the interaction occurs in a thick nonlinear medium comes to our aid. The phase-matching conditions for up-conversion in a thick medium are very strict and serve as a narrow spectral filter ($\sim$0.1-nm bandwidth at 532 nm for a 1-cm-long KTP crystal). If the detected data bandwidth is much lower, further filtering may be required. In addition, the enhancement depends critically on the characteristics of the overall phase function $\phi(\omega)$. It can be eliminated by symmetric phase functions (around $\omega_p/2$), while unaffected by antisymmetric phase functions. Thus, the application of a spectral phase function can be used to fully and reversibly control the up-conversion enhancement. For example, such a phase function can serve as a unique signature of the data-transmitting side. Only when the receiver introduces the opposite phase function is the up-conversion enhancement restored. The phase function can be as simple as a known relative delay or dispersion between the idler and the signal or an arbitrary spectral phase function introduced by the powerful tools of coherent pulse shaping [29]–[31].

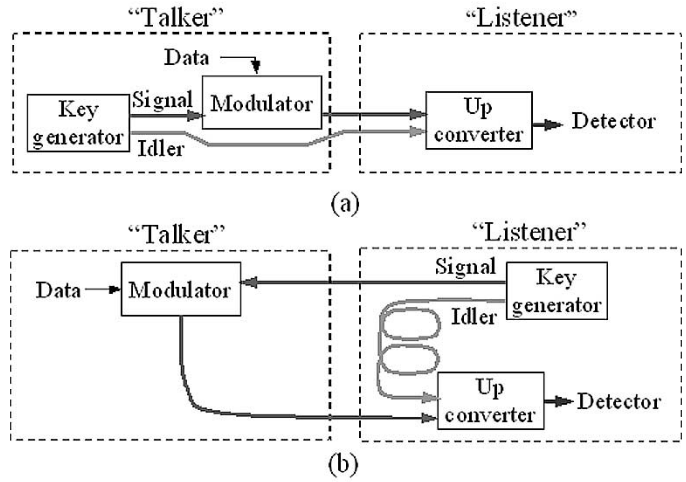

Fig. 2. Schematic configurations for optical direct-sequence communication. The key is generated at the (a) talker side and (b) listener side.

As an example, for a simple spectral phase function, consider the case of a relative delay τ between the signal and the idler fields, which is equivalent to a linear spectral phase function on half of the spectrum. In this case

$$R(\omega_p) \propto \left| \int_0^{\frac{\omega_p}{2}} d\omega' \left|A_s(\omega')\right|^2 e^{i\omega'\tau} \right|^2. \quad (7)$$

As evident from the equivalence to an ultrashort pulse, when the relative delay exceeds the coherence time of the signal field ($\tau \sim 2/\Delta$), up-conversion is dramatically reduced.

We conclude that detection of the up-conversion intensity at the original pump frequency serves as the mechanism for multiplication by the conjugate key at the receiver. The enhancement in the up-conversion intensity occurs only when the signal field combines with its twin idler field, thereby extracting the transmitted data out of the noise. This enhancement can be fully and reversibly controlled by the introduction of a spectral phase function.

C. Single-Channel Communication

In our approach, once broad-band down-conversion is achieved, the signal field is separated from the idler field by means of a spectral filter. We identify the signal field as the key and the idler field as the conjugate key. The main difference between our approach to others in optical and electrical communications is that in our approach, the key is inherently unknown. Thus, the conjugate key must somehow reach the listener (the data-receiving side) together with the data-carrying key in order to enable the extraction of the transmitted data.

Fig. 2 shows schematically two possible communication configurations. The first probably most intuitive configuration, shown in Fig. 2(a), is that the talker (the transmitting side) generates the key and the conjugate key, modulates one of them with data, and sends both of them to the listener. The listener will perform up-conversion and extract the data. Another configuration, shown in Fig. 2(b), is a bit similar to public key encryption. The listener generates the key and the conjugate key and sends only one of them to the talker. The talker modulates the key (probably together with other noises that arrive with the data) and sends it back to the listener. The listener then uses the other key that she previously kept (properly delayed) in order to extract the data via up-conversion.

Note that any type of modulation (amplitude, frequency, or phase) is suitable for data transmission. This statement is obvious in the case of amplitude modulation (AM) but is a bit surprising for frequency modulation (FM) or phase modulation (PM), since minute frequency/phase shifts cannot be detected directly from the broad-band incoherent key (signal). Still, since the up-conversion appears at the sum frequency with a phase that is a sum of the signal and idler phases, a small frequency/phase shift of the signal will cause the same frequency/phase shift of the narrow-band coherent up-converted field, which is easily detected.

D. Optical Code-Division Multiplexing

Our approach for code-multiplexing channels stems from the fact that enhancement in the up-conversion intensity can be controllably and reversibly destroyed by introduction of a spectral phase function; for example, by the introduction of a known amount of relative delay or material dispersion between the signal and the idler fields. This leads us to the multiplexing/demultiplexing configurations depicted in Fig. 3. In the multiplexer configuration shown in Fig. 3(a), every channel modulates the signal field emitted from a broad-band down-conversion source and introduces a unique amount of delay between the signal and the idler. The difference between the unique delays associated with the various channels should be longer than the correlation time of the broad-band signal–idler fields. All channels are then joined together in one fiber and transmitted to the receiver end.

In order for a specific receiver to detect a specific channel, the receiver configuration, shown in Fig. 3(b), will insert the inverse delay to that channel. This will restore the phase relations of this channel only, thus restoring the enhancement in the up-conversion at the original pump frequency. When the up-conversion intensity at the pump frequency is detected, this channel will be prominent above the noise (generated by other channels). Since each receiver detects only one channel and other channels just pass through without disturbance, it is reasonable that after detection the receiver will reinsert the delay in order to leave the situation unchanged for all other channels. A complete demultiplexer will be composed accordingly of many such receivers in cascade.

In our OCDMA scheme, the number of simultaneous channels, each of bandwidth δ that can be accommodated within a total bandwidth Δ is given by

$$N = \frac{1}{2}\frac{1}{\frac{s}{n}}\left(\frac{\Delta}{\delta}\right) \tag{8}$$

where s/n is the minimum allowed SNR, and the major noise source is assumed to be interference caused by other channels.

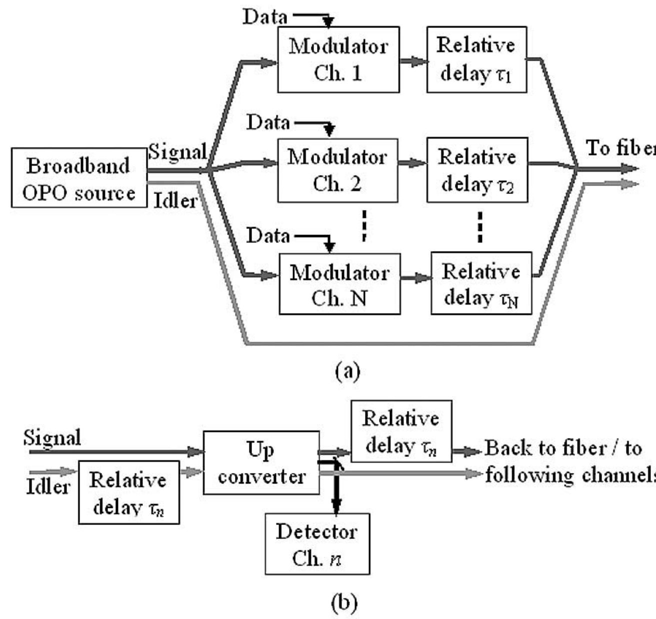

Fig. 3. Schematic configuration of an OCDMA multiplexer and demultiplexer in the case of key generation at the "talker" side. (a) Configuration of an OCDMA multiplexer. (b) Configuration of a receiver for one OCDMA channel.

This result is just a factor of two less than expected in an ideal asynchronous CDMA system, which is due to the fact that in our configuration the key has to be transmitted also. This indicates that the spectral efficiency in our approach can reach $0.5/(s/n)$. It is important to note that since the DS key in our approach is ideal (true white noise), this result is independent of practical constraints, such as lower/upper bounds on the single-channel bit rate.

Note, that in order to achieve the capacity of (8), it is necessary that all channels will share the same key, i.e., either all channels use the same signal and idler emitted by one broad-band down-conversion source or all the sources of all channels are seeded by one noise field. Although a configuration in which every channel has its own independent key is also possible, it suffers from a higher noise level at the receiver due to the existence of multiple keys in addition to multiple channels and, therefore, can support a lower number of channels $(\sqrt{N})$ compared with the number of channels (N) supported by the first optimal configuration.

The multiplexing configuration of Fig. 3 is a generalization of the configuration shown in Fig. 2(a) with the keys generated by the "talker." A similar generalization can be made for the case of key generation by the "listener," as schematically shown in Fig. 4. In this case, the network contains a forward channel for all the "public keys" and a backward channel for returning data. As shown, a user who wishes to receive data (listener) generates his own keys and sends his "public key" into the forward channel of the network. Other users who wish to communicate with that user (talkers) split a part from the forward channel, modulate it with data, and insert it into the backward channel. A talker can also add a spectral phase signature to identify this specific talker–listener connection, but this is not necessary since the distance to that specific talker already serves as a unique delay sig-

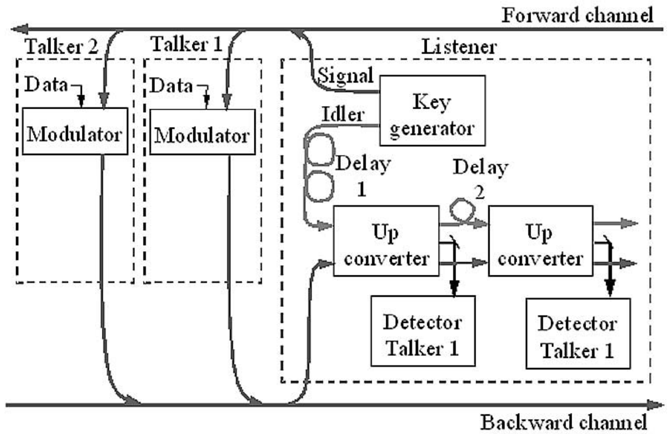

Fig. 4. Schematic configuration of an OCDMA network in the case of key generation at the "listener" side.

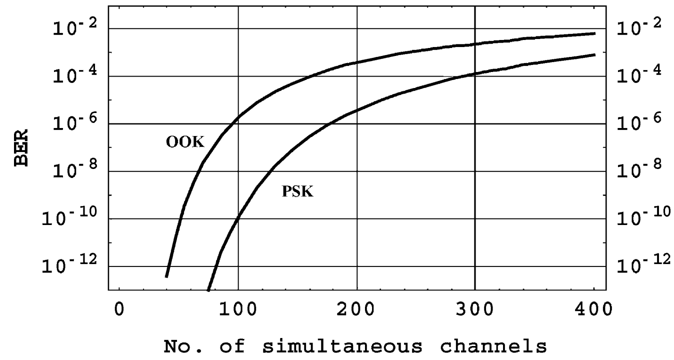

Fig. 5. Calculated BER as a function of the number of simultaneous CDMA channels for OOK and PSK modulations. The single-channel rate is taken to be 1 Gb/s with 4 THz of usable bandwidth for CDMA. The interchannel interference is assumed to be the major noise source and is modeled as a white noise, which is reasonable for a large number of simultaneous channels. No forward-error correction is included.

nature. Listeners will extract the data via up-conversion using their conjugate "private key" after appropriate delay and insertion of the opposite spectral phase. The total capacity remains as given by (8).

IV. Discussion

A. Expected Bit-Error Rate and Data Modulation Possibilities

Equation (8) reflects the relation of the noise level at the receiver of a single channel to the total number of simultaneous channels. In Fig. 5, this relation is translated into bit-error rate (BER) for ON–OFF keying (OOK) modulation with incoherent detection and for phase-shift keying (PSK) with coherent detection. As evident from Fig. 5, coherent PSK yields much better BER results compared with incoherent OOK. This is no surprise, since coherent modulation is known to be preferable in many aspects (BER, power management, reduced nonlinearities, etc.). Albeit, coherent modulation is considered impractical in the optical domain because it requires a local oscillator at the receiver that is phase-locked to the transmitting laser. With our CDMA approach, a reference local oscillator can be easily sent from the transmitter to the receiver. Since all channels share the same down-converted field and the same pump, the pump serves as a local oscillator for all the channels. The pump cannot be sent along with the data as is (mostly because of nonlinearities), but if we "sacrifice" one channel and not modulate it with data, the up-conversion field of that channel will be just a replica of the CW pump field, which can be used as a phase reference for all other channels. Thus, coherent detection can be performed at the price of one less data channel.

Coherent modulation is made possible here due to the fact that all the channels are *optically equal* in the sense that all share the same pump (or up-conversion) and down-converted fields. This fact can be exploited for performing other kinds of optical manipulations. For example, one can think of an optical switching scheme where, after demultiplexing (up-conversion with the appropriate delay for each channel), it is possible to remultiplex the channels in a different order by down-converting them again and rearranging their delays.

B. Privacy Considerations

Generally, spread spectrum communication is considered to be immune to both eavesdropping and jamming. Immunity to eavesdropping comes in two levels: one is the ability to conceal the mere existence of the transmittance in the noise, and the other is the encryption supplied by the use of the key.

The ability to conceal transmission in the noise is preserved in our optical direct-sequence approach, but it is clear that the encryption is lost when the talker generates both keys and sends both to the listener. Indeed, any eavesdropper can listen to the transmission if its existence is known to him or her just by performing up-conversion. The encryption can be restored if the talker introduces an additional overall spectral phase function known only to him or her and the listener, so only the listener can undo this phase function before performing up-conversion.

The "public key" communication possibility seems at first glance to be totally immune to eavesdropping. The conjugate key that is never transmitted is inherently unknown and is never repeated (it is continuously generated) so that an eavesdropper cannot reproduce the conjugate key. Although this statement is correct, an eavesdropper can still listen in on the data transmitted without having the other key. This is due to the fact that the talker does not know the key either and modulates data onto whatever is received within the spectral bandwidth of the key. Thus, if an eavesdropper knows about the communication, she can generate her own set of keys and send one of these keys also to the talker, who will modulate this key also with data. The eavesdropper can now extract the data by up-conversion using her own properly delayed conjugate key. Again, talkers can prevent eavesdropping by introducing a unique spectral phase function known only to them and the listener.

We conclude that the fact that the keys are incoherent and inherently unknown cannot provide additional security to the communication with the previously described schemes, so in order to achieve security of the transmission, one must "encrypt" the key by use of a unique spectral phase function.

C. Chromatic Dispersion

Dispersion is an important optical factor that influences data transmission over a fiber. Generally, the proposed optical DS is expected to be sensitive to dispersion because of the large bandwidths of the signal and the idler and the need to keep their phases intact. This is true for *even* orders of dispersion, and the total usable bandwidth for CDMA communication is limited by the degree of compensation for the even orders; therefore, a good compensation for the second-order dispersion (β_2) is necessary. Yet, as long as the pump bandwidth (i.e., the data bit rate per channel) is not very high, the proposed OCDMA is insensitive to odd orders of dispersion. This is due to the fact that odd orders introduce a spectral phase, which is antisymmetric around the center of the spectrum ($\omega_p/2$), and as clear from (5), the up-conversion intensity is insensitive to it.

As the pump bandwidth (or the single-channel data rate) gets higher, the center frequency is less defined, and odd orders of dispersion start to manifest themselves as residual even orders at the side lobes of the pump. Thus, the even orders of dispersion limit the total usable bandwidth for CDMA, while the odd orders of dispersion limit the single-channel bandwidth.

A numerical calculation using the dispersion parameters of bulk silica shows that after propagating 40 km at the zero-dispersion point, where the second order of dispersion is zero, the total usable bandwidth is $\sim$5 THz (i.e., $\sim$2.5 THz available for data transmission), and the maximal bit rate per channel is $\sim$10 GHz. Note that the limit posed by odd orders of dispersion on the single-channel bit rate does not affect the total capacity of the CDMA connection since, with CDMA, a reduction of the single-channel bandwidth automatically increases the total number of channels, leaving the capacity unchanged.

D. Nonlinear Propagation Effects

Nonlinear effects, such as Brillouin scattering, self-phase modulation, cross-phase modulation, and four-wave mixing, occur when the temporal intensity or the power spectrum in the fiber is high; thus, they are generally minimized by broad-band noiselike fields that minimize the possibility for persisting constructive interferences. It is obvious that once the signal and the idler are "decorrelated" by introduction of some spectral phase function (e.g., a short relative delay), they can be considered as a broad-band noise field, so our OCDMA scheme inherently minimizes nonlinear effects in fibers that can have unwanted influence on the communication.

E. Comparison With Other OCDMA Approaches

The major problem for obtaining OCDMA is that of generating the pseudonoise key. The many attempts to solve this problem can be divided into two categories—a coherent approach and an incoherent approach. The coherent approach [2]–[6] starts from a broad-band coherent source (i.e., a mode-locked laser that emits transform-limited pulses). The key for each channel is then generated by actively shaping the spectral phase in a unique manner through some kind of a pulse-shaping device, which deforms the pulse to mimic a pseudonoise burst. At the receiver, a shaper performs the inverse shaping to recreate the original transform-limited pulse, which is then detected by use of an ultrafast nonlinear thresholder that is sensitive to the pulse peak intensity. The main disadvantage of this approach is that a great deal of the flexibility of CDMA is lost because of the limitations imposed by active pulse shaping. For example, the total number of channels is limited by the number of pixels of the pulse shaper, and the lowest effective bit rate per channel is limited by the spectral resolution of the shaper.

The incoherent approach (with its many versions) [7]–[14], on the other hand, involves an incoherent broad-band source. Although such a source emits "true noise," the phase of the emitted field is not known, so only intensity manipulations are possible. This makes the incoherent approach robust in the sense that it is relatively immune to phase changes due to propagation effects, but since the incoherent approach is inherently unipolar, the cross correlation of different keys cannot average out to zero. Thus, the noise level in incoherent CDMA systems is much higher, which causes the performance to deteriorate severely as the number of users grows [3], [11]. For this reason, the capacity of incoherent CDMA systems is inherently and significantly lower than that of coherent ones ($\sqrt{N}$ channels compared with N channels in the coherent approach).

Our OCDMA approach can be considered as some kind of a hybrid that alleviates some limitations of both approaches. It is a coherent approach in the sense that it relies on the coherent phase relation between the signal and the idler (the key and its conjugate) so that the capacity is comparable with that of the coherent approach. Yet, the key is a true white noise that is passively generated, minimizing nonlinear effects and preserving the full flexibility of CDMA. The only drawback of the proposed OCDMA compared with the coherent approach is the need to transmit the key to the receiver, whereby 50% of the bandwidth is "wasted." Fortunately, even this drawback has a positive side because it leads to the insensitivity to odd orders of dispersion.

V. Concluding Remarks

In this paper, we presented novel coherent optical direct-sequence communication and CDMA configurations that exploit the special spectral phase correlations within the spectrum of broad-band parametrically down-converted light in order to generate an *ideal* set of key and conjugate key. Extraction of the encoded data is performed by the inverse process of parametric up-conversion. The proposed scheme benefits from the high capacity associated with coherent optical processing, while avoiding the limitations of active pulse shaping, thereby preserving the full flexibility of CDMA.

For the proposed optical CDMA schemes to be practical, it is obviously necessary to have a parametric source that generates the broad-band signal and idler fields with high efficiency at low pump powers. Since the nonlinear interaction is weak, an oscillator in a high-finesse cavity would appear to be a reasonable choice. Unfortunately, in such a cavity, mode competition significantly narrows the spectrum of the actual oscillation even when phase matching allows broad oscillation. Consequently, in order to achieve broad-band oscillation, the cavity should be specially designed to suppress narrow-band oscillation while allowing broad-band oscillation to develop. We are currently investigating such a source and expect to report on the design, performance analysis, and experimental results in the near future.

APPENDIX I
PHASE AND AMPLITUDE CORRELATIONS IN PARAMETRIC DOWN-CONVERSION

In order to understand the signal–idler correlation in parametric down-conversion, we adopt the theoretical treatment developed for three-wave mixing that appears in [18, Ch. 6, pp. 67–85]. We start from the standard equations of three-wave mixing describing the down-conversion process. Under the simplifying assumptions of a lossless medium and perfect phase matching, we have

$$\begin{aligned}\frac{\partial A_s}{\partial z} &= -i\kappa A_i^* A_p\\ \frac{\partial A_i}{\partial z} &= -i\kappa A_s^* A_p\\ \frac{\partial A_p}{\partial z} &= -i\kappa A_s A_i\end{aligned} \tag{9}$$

where A_s, A_i, and A_p are the slow-varying amplitudes of the signal, idler, and pump, respectively, and κ is the nonlinear coupling, which is related to the nonlinear coefficient d (in MKS units) via

$$\kappa = \frac{d}{2}\sqrt{\frac{\mu_0}{\varepsilon_0}\frac{\omega_s\omega_i\omega_p}{n_s n_i n_p}} \tag{10}$$

where n_x is the refractive index and ω_x the frequency of field $x\,(x = s, i, p)$. ε_0 and μ_0 are the vacuum dielectric permeability and magnetic permeability, accordingly. Our interest is in the phase correlations between the three amplitudes, so a transformation to polar coordinates seems reasonable

$$\begin{aligned}\frac{\partial R_s}{\partial z} + iR_s\frac{\partial \theta_s}{\partial z} &= -i\kappa R_i R_p \exp\left[i(\theta_p - \theta_s - \theta_i)\right]\\ \frac{\partial R_i}{\partial z} + iR_i\frac{\partial \theta_i}{\partial z} &= -i\kappa R_s R_p \exp\left[i(\theta_p - \theta_s - \theta_i)\right]\\ \frac{\partial R_p}{\partial z} + iR_p\frac{\partial \theta_p}{\partial z} &= -i\kappa R_i R_s \exp\left[-i(\theta_p - \theta_s - \theta_i)\right]\end{aligned} \tag{11}$$

where we substituted $A_x = R_x \exp(i\theta_x)$ for all three waves. We now substitute $\Delta\theta = \theta_p - \theta_s - \theta_i$ into (11) and separate the real and imaginary parts to yield

$$\begin{aligned}\frac{\partial R_s}{\partial z} &= \kappa R_i R_p \sin\Delta\theta\\ \frac{\partial R_i}{\partial z} &= \kappa R_s R_p \sin\Delta\theta\\ \frac{\partial R_p}{\partial z} &= -\kappa R_s R_i \sin\Delta\theta\\ \frac{\partial \Delta\theta}{\partial z} &= \kappa\cos\Delta\theta\left[\frac{R_i R_p}{R_s} + \frac{R_s R_p}{R_i} - \frac{R_i R_s}{R_p}\right].\end{aligned} \tag{12}$$

Substituting the first three parts of (12) into the fourth and performing some simple algebraic manipulations yields

$$\frac{\sin\Delta\theta}{\cos\Delta\theta}\frac{\partial\Delta\theta}{\partial z} = \frac{1}{R_s}\frac{\partial R_s}{\partial z} + \frac{1}{R_i}\frac{\partial R_i}{\partial z} + \frac{1}{R_p}\frac{\partial R_p}{\partial z}. \tag{13}$$

Equation (13) is equivalent to

$$-\frac{\partial}{\partial z}\left[\ln(\cos\Delta\theta)\right] = \frac{\partial}{\partial z}\left[\ln(R_s R_i R_p)\right] \tag{14}$$

which can be solved immediately to obtain

$$\cos\Delta\theta = \frac{C_1}{R_s R_i R_p} \tag{15}$$

where C_1 is an integration constant. Since the phase difference $\Delta\theta$ is real, it is clear that the constant C_1 is bound by the initial values of the field amplitudes $R_x[0]$, according to

$$0 \le |C_1| \le R_s[0]R_i[0]R_p[0]. \tag{16}$$

In most practical cases, at least one of the fields A_s, A_i, and A_p is initiated by spontaneous emission noise, so it is practically zero. Thus, as the field amplitudes grow, the denominator of (15) becomes much larger than the nominator, so the value of the constant C_1 becomes irrelevant, and, for all practical purposes, we obtain $\cos\Delta\theta = 0$. We thus find that the phases of the signal and the idler are correlated according to

$$\theta_s + \theta_i = \theta_p - \frac{\pi}{2}. \tag{17}$$

If we choose to define the pump phase as $\theta_p = \pi/2$, we get

$$\theta_s = -\theta_i. \tag{18}$$

Consequently, we find that the phase of an idler mode in an OPO cavity is opposite to that of the corresponding signal mode. The absolute value correlation between the signal and the idler can be understood from the fact that they are symmeftric in (11). Thus, if the initial conditions are symmetric, then this symmetry will be preserved.

APPENDIX II
BROAD-BAND PHASE MATCHING

In Section III-B, we showed that the temporal resolution obtained by a parametric source is equal to that obtained by a transform-limited pulse. Consequently, if we intend to explore and exploit this feature, we should develop an OPO/OPA oscillating over the widest possible spectrum. A necessary condition for a broad-band oscillation is phase matching over a broad wavelength range. It is generally known that when the signal and the idler are close to degeneracy (i.e., $\omega_i \approx \omega_s \approx \omega_p/2$), the type I phase matching (where the signal and the idler have the same polarization) becomes broad. This is depicted in the graph in Fig. 6(a), which shows the phase mismatch $(\Delta k \equiv k_p - k_s - k_i)$ as a function of wavelength for a periodically polled KTP crystal pumped at 532 nm. As evident, to first-order approximation in wavelength, the phase-matching condition for wavelengths close to that point is the same. One can expect a spectral width of tens of nanometers around 1064 nm for a crystal length of 1 cm.

Yet, much broader phase matching is possible if the pump is tuned so that the degeneracy point (at the wavelength of $\lambda = 2\lambda_p = 4\pi c/\omega_p$) coincides with the point of zero dispersion of the crystal. At the zero-dispersion point, the second derivative of the index of refraction with respect to the wavelength vanishes, so the index of refraction is predominantly linear in wavelength. It can be shown that when the index of refraction is linear, any two complementary wavelengths are phase matched. Higher orders of dispersion will limit the phase-matching bandwidth but only to fourth order in wavelength, since odd orders of dispersion do not affect phase matching. Thus, with zero dispersion, one can obtain ultrabroad phase matching, of up to hundreds of nanometers, as depicted in Fig. 6(b) for a BBO crystal pumped at 728 nm.

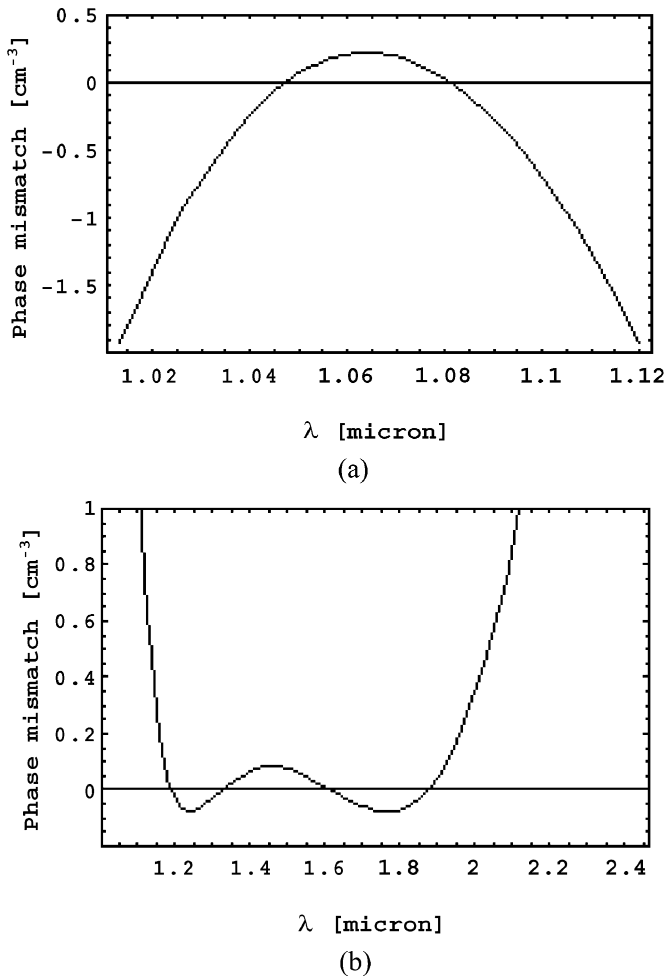

Fig. 6. Broad type I phase-matching situations. (a) Typical phase mismatch as a function of wavelength near the degeneracy point (calculated here for a periodically polled KTP crystal pumped at 532 nm). (b) Ultrabroad situation when the pump is tuned such that the down-conversion center wavelength coincides with the zero-dispersion wavelength of the crystal (as calculated here for a BBO crystal pumped at 728 nm).

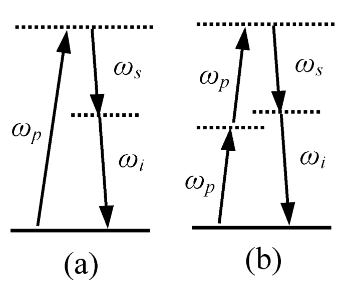

Fig. 7. Feynman diagrams of possible nonlinear mechanisms for CDMA. (a) Three-wave mixing. (b) Four-wave mixing.

Appendix III
Using Higher Order Nonlinear Processes

In the text, we considered a CDMA scheme based on the process of three-wave mixing as the mechanism for generating two broad-band conjugate fields. This process can be schematically depicted by the Feynman diagram shown in Fig. 7(a), which can be interpreted quantum mechanically as the conversion of one high-energy pump photon into two low-energy signal and idler photons. Yet, higher order nonlinear processes can perform this task just as well, e.g., with four-wave mixing, as depicted in Fig. 7(b), which can be interpreted as the conversion of two pump photons into two broad-band signal and idler photons. Generally, any process in which n pump photons are converted into two photons can be considered as the basis for our CDMA scheme, though it is unlikely that such higher order nonlinearities will be preferable because of their weakness and added complexity.

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