Analysis of an optical frequency-hop encoder using strain-tuned Bragg Gratings

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Abstract

We propose fast optical frequency-hop code division multiple access (FH-CDMA) for high capacity local area networks. Encoding and decoding are achieved by tunable fiber gratings.

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Introduction

In optical communication systems, fiber gratings have been used to perform chromatic dispersion compensation, gain equalization, pulse compression, soliton pulse shaping, add/drop switching and channel filtering for wavelength division multiplexing (WDM) systems [1,2]. Recently Chen *et al.* studied a multiple grating structure that could be used to achieve spectral slicing in WDM and CDMA systems [3]. In this paper we propose a tunable multiple-grating fiber for frequency-hop encoding-decoding operations. To our knowledge, this is the first proposal for frequency-hop code division multiple access (FH-CDMA) in optical fiber local area networks.

CDMA techniques fall into four broad categories: direct sequence (DS), frequency encoded (FE), time hopping (TH) and frequency hopping (FH). Optical CDMA systems have been proposed for the first three [4-6]. The agility of modern radio transmitters to quickly change transmission frequencies for FH-CDMA has no obvious corollary in optics. The use of multiple Bragg gratings, however, has the effect of introducing a delay among reflected frequencies (depending on the position of the Bragg grating) that can be interpreted as a FH-CDMA "hopping" pattern. By use of piezo-electric devices, the order of the center frequencies of the Bragg gratings can be changed, effectively changing the hop pattern and therefore allowing for programmable codes (Figure 1). An important feature of every CDMA system is the architecture of the encoder/decoder pair, the functionality of which should provide for an efficient encoding and correlation of the code sequences. In this paper, we present the tradeoffs involved in the design of the encoder-decoder pairs. We first select a family of suitable codes for simulation of the FH-CDMA communication system. We then address the design issues of the encoding device. Apodization of the Bragg gratings is required to perform accurate and dense spectrum slicing. Optimization of code performance and spectrum utilization is performed. Finally, the achievable performance is evaluated in term of auto- cross-correlation properties.

Frequency-hop signal

In FH-CDMA communications each information bit from user *m* is encoded into a signal $c_m(\omega, t)$ that corresponds to a code sequence of N chips (or pulses) representing the address of that user. The k^{th} pulse is thus modulated with frequency f_k about the carrier frequency f_c;

$$f_k = y(k)\frac{B}{N} \qquad k = 1,\ldots,N \qquad (1)$$

where B is the signal bandwidth, $y(k)$ is the placement operator (also called the frequency hop pattern). The placement operator is a sequence of N ordered integers determining the placement of frequencies in various time slots. A convenient way of representing a frequency hop pattern is through a $N\times N$ matrix representing the time and frequency axis (Figure 2). We adopt the hyperbolic codes [7], derived based on congruence theory for satellite and mobile FH-CDMA communications systems, having the following placement operator

$$y_{l,a} \equiv \frac{l}{k} + a(\mathrm{mod}\,N) \quad \text{for } k,l,a = 1,2,\ldots,N-1 \ (2)$$

where k denotes the frequency bin number; and the pair (l, a) defines the user code, leading to (N-1)x(N-1) independent codes. Thus, with N=11, 100 independent codes can be obtained with first two placement operators given by $y_{1,1}$=[1 2 7 5 4 10 3 9 8 6 11] (user 1) and $y_{2,1}$=[1 3 2 9 7 8 5 6 4 11 10] (user 2).

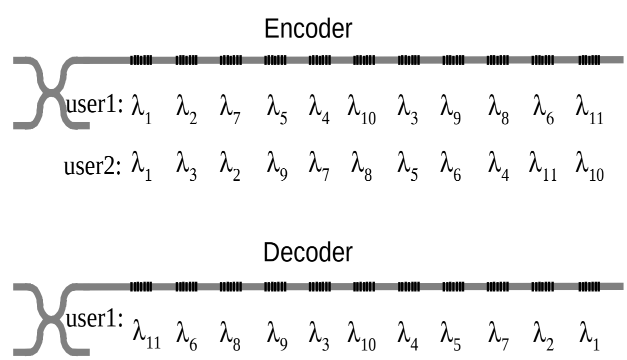

Figure 1: The encoder/decoder.

As in any CDMA system, the selected users' codes must satisfy the following three funda-

mental conditions. Firstly, the peak of the auto-correlation function

$$R_{c_m}(s) = \sum_{i=0}^{N} c_m(i) c_m(i-s) \quad -N+1 \le s \le N-1 \quad (3)$$

should be maximized for each code. Secondly, the side-lobes of this function should be minimized. Finally, the cross-correlation function

$$R_{c_m,c_p}(s) = \sum_{i=0}^{N} c_m(i) c_p(i-s) \quad -N+1 \le s \le N-1 \quad (4)$$

of each pair of sequences c_m and c_p should be minimized. These conditions constrain the physical positioning of the gratings on the fiber as well as their bandwidth. The relative distances between the gratings must be chosen to satisfy a given level of auto- and cross-correlation between the codes. This distance in turn determines the achievable bit rate. Equations (3) and (4) will be used later to evaluate the auto- and cross-correlations for the proposed devices.

The encoding device

The encoding device consists of a series Bragg gratings all written at the same wavelength λ_B. Each grating can be tuned independently using piezo-electric devices to adjust the Bragg wavelength from λ_B to a given wavelength defined by the corresponding placement operator. The advantage of this approach is that only one phase mask is needed to write any encoder or decoder. The tuning of each device will determine the code used.

As an example, user two will tune the first grating to λ_1, the second to λ_3, ..., and the eleventh to λ_9 (see Figure 1). The gratings will spectrally and temporally slice an incoming broadband pulse into several components as demonstrated by Chen *et al*. [3]. In the decoder, the peak wavelengths would be placed in reverse order to achieve the decoding function (matched filtering). The reflected pulses are equally spaced in time, which is precisely the round-trip propagation time between two gratings. The time spacing, the chip duration, and the number of gratings will limit the data bit rate of the system, *i.e.* all reflections should exit the fiber before the next bit enters.

For uniform gratings, the optical fiber is required to stretch approximately $\Delta L = 2N\lambda_B$, or 34 µm for N=11. Tuning Bragg gratings with typical strains of 0.5% results in a nominal spacing of L_0=1cm between the beginning of successive gratings. The total round trip time in the grating structure will therefore be $2(N-1)L_0 n_0/c$ leading to a maximum transmission frequency of 1 Gbs.

Each grating bandwidth must however be such that the time overlap of the reflected pulses does not degrade the cross-correlation function. At a 1 Gbs data transmission rate, the chip rate is 11 Gbs. The required grating bandwidth is thus in excess of 25 GHz. Furthermore, in FH-CDMA, the frequency components are assumed to have a rectangular shape. Recently, Helge *et al*. [8] demonstrated a grating with a sinc apodization that approaches the ideal rectangular reflectivity characteristics. To achieve nearly disjoint and high-density frequency slices, several apodization profiles have been simulated in this work.

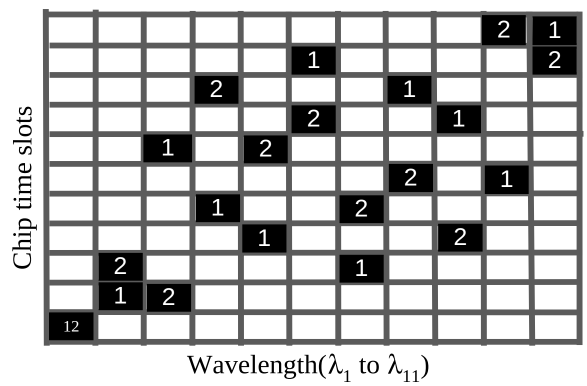

Figure 2: Frequency-hop patterns 1 and 2.

The Gaussian profile performs high main lobe reflectivity, (about 20 dB over the side lobes), but occupies relatively large bandwidth reducing the possible number of slices. The near ideal rectangular reflectivity can be achieved only by using 1) an infinitely long complex grating with a sinc apodization including many side lobes, 2) the inverse Fourier transform of the raised cosine Hamming window or 3) the Blackman window. In our case, the grating length and separation are crucial parameters, limiting the data bit rate.

We found that for finite limited length, the sinc main lobe apodization can outperform the Gaussian apodization, with –25 dB side-lobes. Figure 3a) depicts the reflectivity of 11 main lobe sinc apodized gratings, *i.e.* user code one. The central resonance wavelengths of these gratings are selected allowing the overlapping between the first and the second side lobes of successive gratings. The time delay between the frequency components is presented in the Figure 3c), which clearly represents the frequency-hop pattern of code one (see Figure 2). Note that the horizontal segments in the group delay curves correspond to the central frequency intervals of the reflected slices. It demonstrates that these frequencies are instantaneously reflected, with no appreciable travel time

in the fiber. The side lobes, in contrast, have long delay times, but lower energy (-25dB).

To estimate the performance of the proposed FH-CDMA encoder-decoder we calculate its achievable auto- and cross-correlation functions versus the ideal case. Figure 4 shows that the device can efficiently perform interference rejection. The auto- correlation presents a high peak, and the cross-correlation between codes one and two only slightly exceeds the ideal case. In simulations we observed that the recombination of the auto-correlation peak is sensitive to the inherent delay between the central and near edge frequencies of each grating reflection main lobe [7]. This intra-band delay is the same for the reflection off the encoder and the decoder. This effect is thus amplified by the double reflection, as the encoder-decoder pair are not true conjugates. Chirped gratings are good candidates to compensate for this effect. The auto-correlation nonetheless presents an easily identifiable peak.

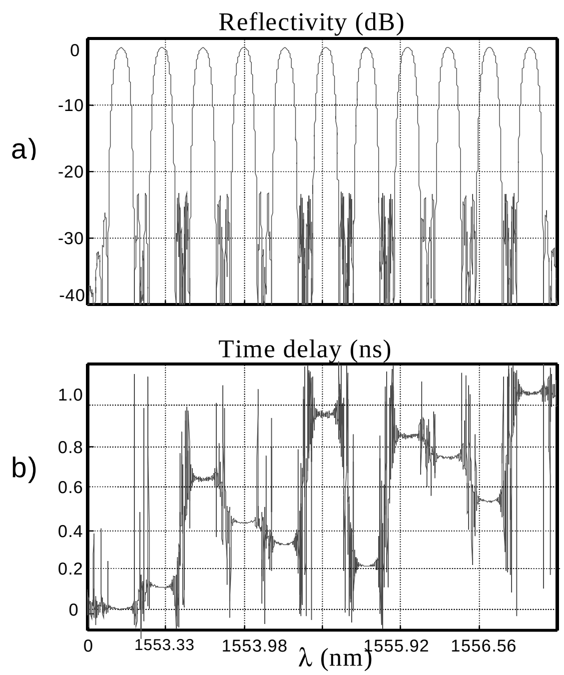

Figure 3: a) Reflectivity, b) group delay

Conclusion:

We proposed and analyzed a novel FH-CDMA encoding device. We selected suitable apodization to perform accurate spectral slicing. Tunable multiple gratings can efficiently detect the desired user, with low cross-correlation (or cross-talk) between the medium sharing users. No chip synchronization is required. The proposed device has the advantage of one design for all encoders and decoders, *i.e.* one fabrication set-up, with programmable codes via piezo-electric tuning.

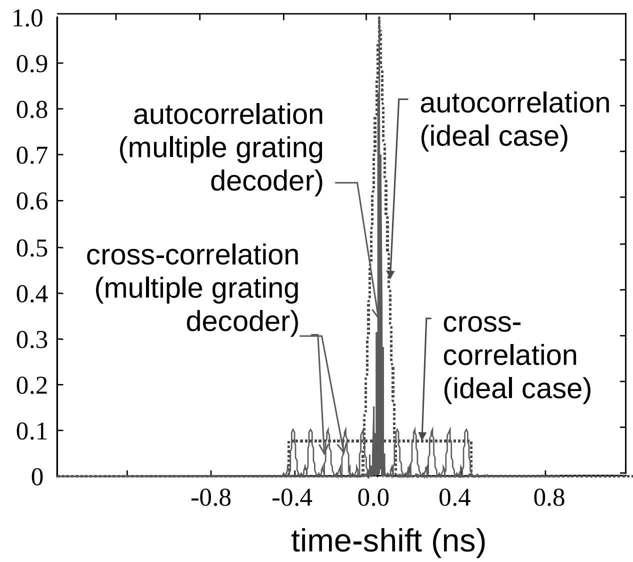

Figure 4: Auto- and cross-correlation.

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