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Superstructured gratings enable OCDMA/WDM compatibility

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Optical-code-division multiple access (OCDMA) technology based on superstructured fiber Bragg gratings for code generation and recognition offers great promise for a variety of network applications, particularly in the metro and access sectors. Wavelength selectivity means it is inherently compatible with WDM technology and can simultaneously support different coding schemes, repetition rates, and wavelength channels

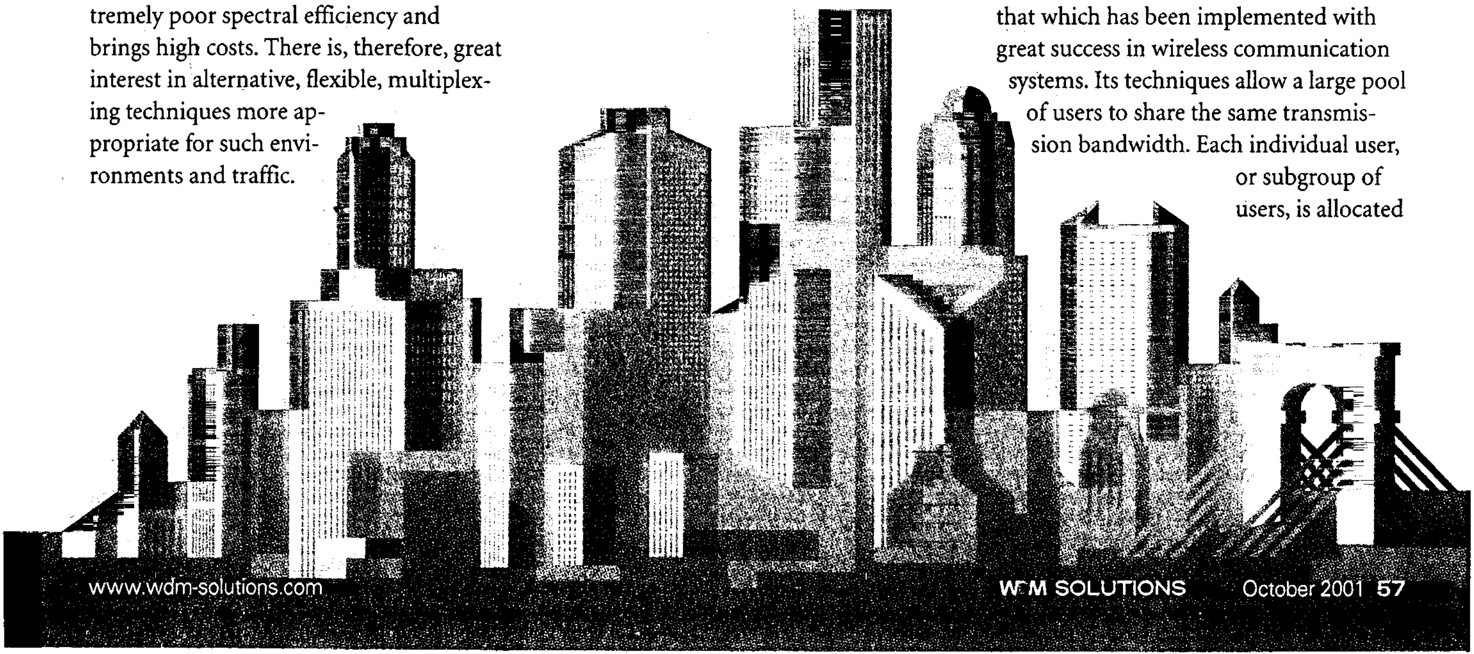
A clear requirement is emerging in the design of future metropolitan and access networks for broadband access techniques capable of supporting more than 100 independent optical channels, each operating at bit rates of 1 Gbit/s and above. Conventional optical multiplexing techniques such as dense wavelength-division multiplexing (DWDM) are likely to struggle, from both technological and economic perspectives, to achieve such fine channel granularity. The problems are compounded by the bursty nature of packet-based services, such as the Internet, in which average data rates per user are frequently two orders of magnitude lower than the required peak rate.

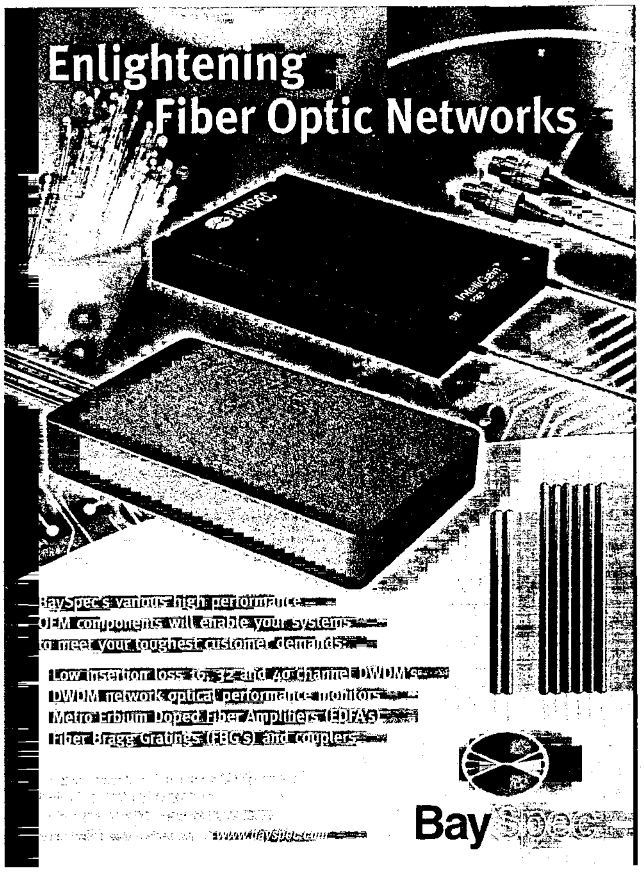
Provisioning of a dedicated wavelength channel per user makes for extremely poor spectral efficiency and brings high costs. There is, therefore, great interest in alternative, flexible, multiplexing techniques more appropriate for such environments and traffic.

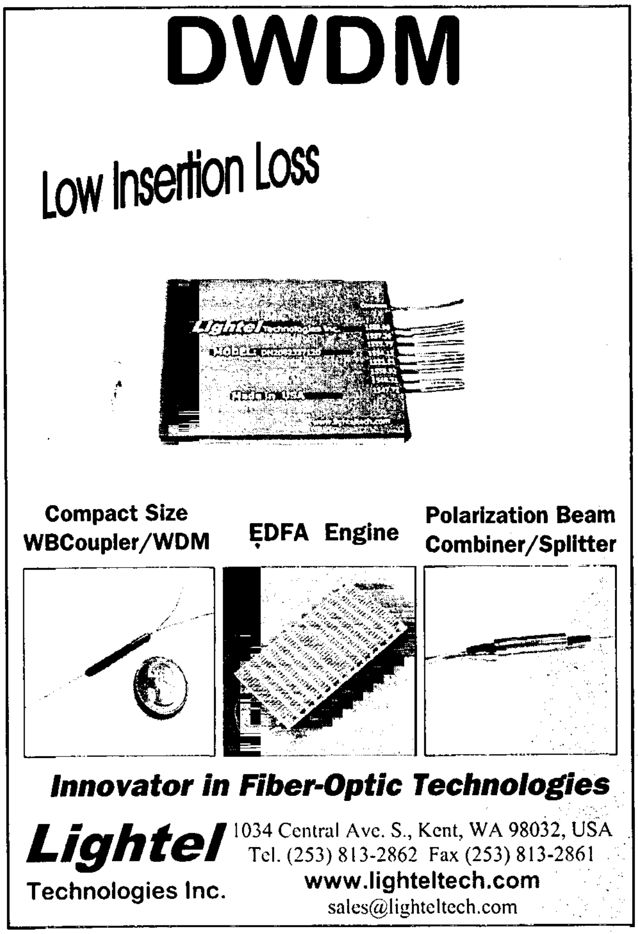
DISRUPTIVE POTENTIAL

Optical-code-division multiple access (OCDMA) is one such alternative technique, which, on the face of it, seems far more suited to such granular applications. It promises a variety of attractive features for network operators relative to the more conventional wavelength-division multiplexing, time-division multiplexing, and associated optical access techniques. Its features include asynchronous operation, flexible bandwidth management, improved system security, and the potential for much higher levels of connectivity and network scalability, among others.

Optical-code-division multiple access is a spread spectrum technique similar to that which has been implemented with great success in wireless communication systems. Its techniques allow a large pool of users to share the same transmission bandwidth. Each individual user, or subgroup of users, is allocated







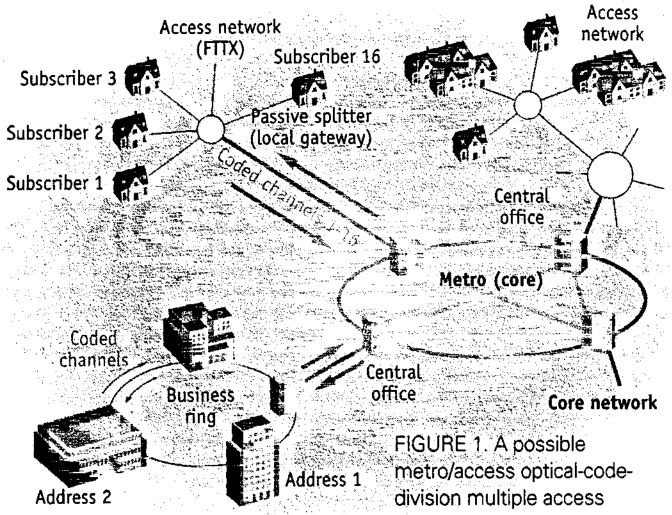


FIGURE 1. A possible metro/access optical-code-division multiple access network architecture would allow a large pool of users to share the same transmission bandwidth.

a specific address that can be used to label bits that are either to be transmitted to the user, or to be transmitted by the user (see Fig. 1).

The optical encoding is ordinarily performed either in the time domain, called direct sequence (DS-OCDMA), or in the frequency domain, called frequency hopping (FH-OCDMA). In DS-OCDMA, each data bit to be transmitted is defined by a code composed of a sequence of individual pulses, referred to as chips. Coded bits are then broadcast onto the network and will only be received by users having a receiver designed to recover data bits encoded with that specific address. In FH-OCDMA, the carrier-frequency of the chips is changed according to a well-defined code sequence that can again be unambiguously identified by an appropriate receiver.

One of the key issues in OCDMA is the development of practical techniques that can reliably generate and recognize appropriate code sequences. Different technical approaches to the coding/decoding process have been demonstrated to date, including those based on splitting, delaying, and recombining pulses in the time domain using, for example, arrays of fiber delay lines, planar lightwave circuits, or arrays of fiber gratings.

Recently, however, superstructured fiber-Bragg-grating technology has emerged as an attractive and highly flexible route to produce high-performance and potentially low-cost optical coders and decoders for DS-OCDMA. A superstructured fiber Bragg grating (SSFBG) is defined as a standard fiber grating—that is to say, a grating with a rapidly varying refractive index modulation of uniform amplitude and pitch—onto which an additional, slowly varying amplitude/phase modulation (corresponding to a specific CDMA code) has been imposed along its length.

In the low grating reflectivity limit, in which the light penetrates the full grating length, the optical frequency response of the grating is given simply by the Fourier transform of the spatial refractive-index modulation profile of the grating. As a result, the shape of the impulse response directly follows the shape of the superstructure imposed upon the grating. Short pulses reflected from the grating are reshaped into pulse sequences with the same form as the superstructure profile imprinted into the grating (see Fig. 2). Thus, spatial information can be written and stored within the core of the fiber, and read out directly into the time domain using a short optical pulse. Coded pulse sequences can be generated by this means and then used to identify individual users/channels within the system.

Code recognition is obtained by matched filtering of the resulting coded signal, using a decoder grating with the time reversed (conjugate) impulse response to that of the encoder grating. Such an impulse response is readily obtained using a grating with a spatially reversed superstructure profile relative to that of the encoder grating—in other words, by using a grating with exactly the same refractive-index profile as the encoder grating, and by illuminating it from the other end.

When the encoder and decoder gratings are correctly matched, the matched filtering process results in the generation of a pulse in the time domain that has the same shape as the code's autocorrelation function. When an "incorrect" matched filter is used, that is, a code corresponding to another user of the system, the pulse generated takes the shape of the cross-correlation of the two codes.

To get reliable operation of the system, it is important that each user can recognize data bits encoded with his or her particular code, and does not mistakenly receive bits intended for other users. To achieve this, it is necessary to restrict the allocation of code sequences to only a subset of the possible code sequences that have both distinct, well-defined autocorrelation characteristics (ideally a single well-defined peak with a width of order-of-the-chip duration), and mutually low cross-correlation characteristics.

The identification of suitable code sets has received much attention in the context of mobile communications. Code sequences, such as the M-sequence, Gold, and Kasami codes, can be generated using established mathematical procedures. Such code sequences have been used extensively in the radio communications fields and many of these coding schemes can also be applied to the case of OCDMA systems.

A key issue for OCDMA systems is to maximize the number of users that can be supported at any time on a system before multiple-access interference (MAI) between the individual channels limits the system's performance. Obviously, the greater the number of users that can be simultaneously supported, the better the system. The degree of MAI between channels is a strong function of the code

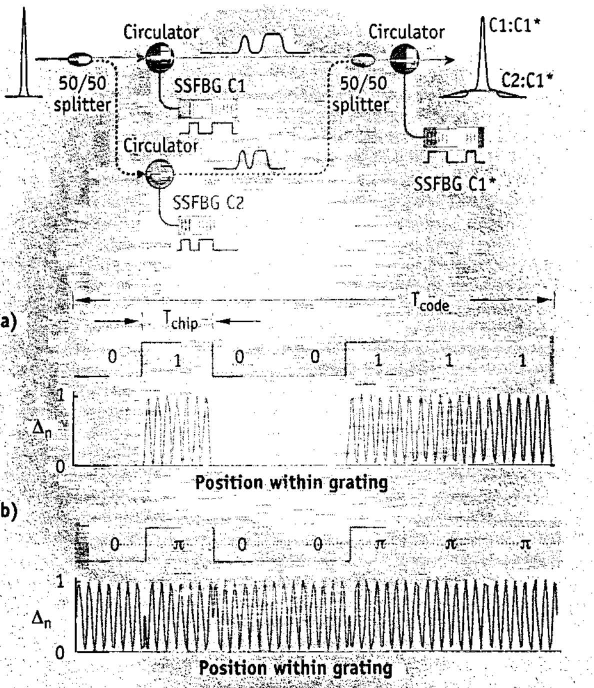
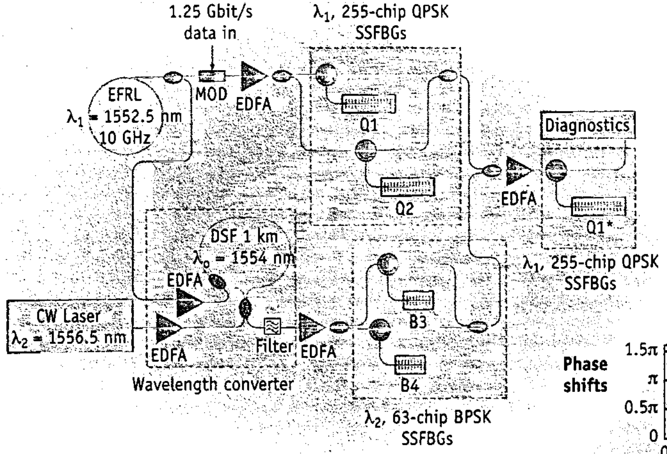


FIGURE 2. In one version of OCDMA, pulse encoding and decoding is performed by superstructured fiber Bragg gratings (top). Typical temporal codes and their corresponding refractive index modulation profiles along the grating structure are also shown (bottom). An amplitude-modulated (unipolar) code SSFBG (bottom, a) contrasts with a phase-modulated (bipolar) code SSFBG (bottom, b). The slowly varying spatial structure at the chip period defines the temporal code and the more rapidly varying periodic modulation defines the Bragg wavelength of the grating.



length (that is to say, the total number of chips in the code) and the physical nature of the coding used.

Unipolar coding, for example, in which only the amplitude of the chips is modulated, offers very limited performance in terms of MAI. However, optical phase-coding approaches, such as bipolar phase coding, allow for interferometric cancellation of parts of the auto/cross-correlation signals, giving substantially improved system performance. It is also possible to use nonlinear thresholding devices at the receiver to provide further significant resilience to MAI in DS-OCDMA systems. It is likely that more than 10 users per wavelength channel will prove physically viable using such approaches.

While the concept of DS-OCDMA using SSFBGs is relatively straightforward, it is only in recent years that fiber-Bragg-grating fabrication technology has advanced to the point that the concept could be tested in practice in the laboratory. By using advanced techniques, such as the continuous

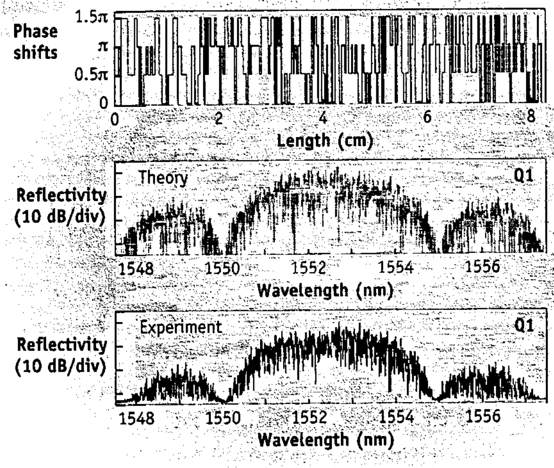


FIGURE 3. An experimental setup with four coded data channels, including quaternary phase-shift keying (QPSK) and bipolar phase-shift keying (BPSK) (upper left). The phase-modulation profile, and spectral-reflectivity profiles (theory and experiment) for the 255-chip, 320-Gchip/s quadrature SSFBG Q1 are shown (lower right).

scanning method, it is now possible to write gratings with both accurately controlled, and suitably complex, amplitude and phase superstructures for OCDMA applications.

It is worth noting that the precision allowed by this fabrication technique is derived from the exposure process itself, and is not limited by the current resolution limits and device lengths imposed by phase-mask technology. Moreover, recent startup companies have extended such high precision grating writing techniques to allow for commercial production of superstructured fiber Bragg gratings.

EXTENDING CODE TECHNIQUES

The first experimental demonstration of an OCDMA transmitter and receiver based on SSFBG technology was reported in 1998.[1] In these experiments seven-chip, unipolar codes were generated and decoded. This was followed, in 1999, by the first demonstration of an optical-phase-based coding scheme, which again used relatively short, eight-chip, code sequences.[2] Further progress in the superstructured fiber Bragg grating-based OCDMA technique has followed, and has increased rapidly this past year.

In the post-deadline session at the 2001 Optical Fiber Communications conference (March; Anaheim, CA), we reported extension of the technique to far-longer code sequences (255 chips), at higher chip rates (320 Gchip/s), and at far-higher levels of phase coding than had previously been possible.[3] Note that these code lengths are more than four times longer than had been previously generated using any alternative technological approach.

Perhaps most significantly in these experiments, we showed that the superstructured fiber Bragg grating OCDMA approach, by its nature, is fully compatible with conventional WDM techniques. In our experimental WDM/OCDMA setup, pulses from a 2.5-ps, 10-GHz, modelocked erbium fiber-ring laser (EFRL), operating at 1552.5 nm, were first split using a coupler into two separate fibers (see Fig. 3).

The first of these outputs was modulated to provide a pseudorandom data sequence of 2.5-ps pulses at 1.25 Gbit/s. The second output was wavelength converted to provide a 10-GHz train of high-quality, 3.5-ps pulses at 1556.5 nm. The individual pulse streams at the two wavelengths were then reflected off one of four coding gratings to generate four separate coded data channels.

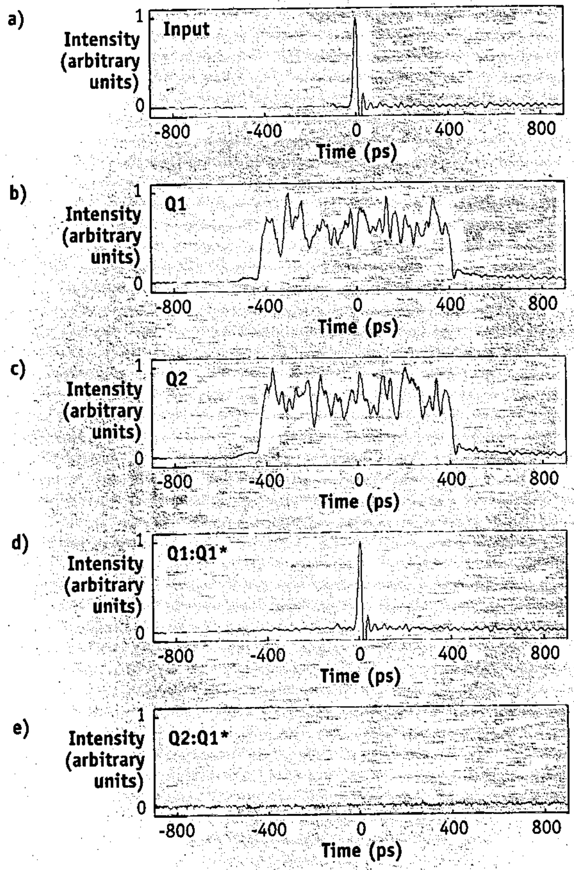


FIGURE 4. Oscilloscope trace measurements were made for: 2.5-ps soliton input pulses (a), the encoded waveform after reflection from SSFBG Q1 (b), the encoded waveform after reflection from SSFBG Q2 (c), the results of matched filtering for the grating combinations Q1:Q1*(d), and after matched filtering for the grating combination Q2:Q1* (e). The time resolution of the measurement was approximately 20 ps.

The 1.25-Gbit/s 1552.5-nm channels were encoded with either one of two "orthogonal" 255-chip, 320-Gchip/s, family A quadrature code sequences (Q1, Q2). The 10-GHz channels at 1556.5 nm were encoded with either one of two 63-chip, 160-Gchip/s, bipolar code sequences (B3, B4) corresponding to two "orthogonal" Gold code-sequences.

All four channels were combined into a single fiber and the resulting signal fed onto a decode grating matched to the particular channel that we wished to decode. (These gratings are correspondingly denoted by Q1*, Q2*, B3* or B4*). Note that the decode grating provides both wavelength channel selection as well as the decoding function for "in-band" signals.

The oscilloscope trace of the coded Q1 channel was obtained by reflecting 2.5-ps short pulses (see Fig. 4) from grating Q1. Although the individual features of the coded sequence are too short to be resolved (each chip has a length of 3.2 ps and the detection system has approximately 20-ps resolution) it is clear that the coding grating spreads the incident 2.5-ps pulse over a time period of approximately 800 ps as expected.

The corresponding oscilloscope trace when grating Q2 is used for encoding was also obtained. For convenience, we denote the individual matched filters to the individual codes using the notation Q1*, Q2* where, for example, Q1* is the matched decoder to grating Q1. We plot the decoded response of grating Q1* to code sequence Q1, denoted Q1:Q1* where it is seen that a short chip length pulse on a very low-level pedestal background is obtained, providing a very high-quality pattern recognition signal.

We plot the response Q2:Q1* (an incorrect code matching) and no discernible recognition signature is observed as expected for two orthogonal codes. Similarly high quality recognition signals were obtained for other combinations of the code grating pairs (for example, Q2:Q2* and Q1:Q2*). Bit-error rate measurements made on the individual 255-chip channels confirmed that error-free performance of the system with four separate operating channels could be readily achieved in the presence of various combinations of interfering channels.

These recent experiments highlight the potential for using superstructured fiber-Bragg-grating technology for WDM/OCDMA applications. The technology is clearly still at an early stage of development; however, the progress to date looks most encouraging. If the approach should ultimately prove capable of supporting a significant number of users at reasonable cost, then it would be of great interest for a number of important metro and access network applications.

The results also show that the superstructured fiber-Bragg-grating approach provides an extremely powerful and flexible way of performing elementary, all-optical processing functions. It should also be appreciated that the ability to control the phase and amplitude of an optical pulse opens a far greater range of possibilities than just OCDMA. For example, we have already demonstrated the use of superstructured fiber Bragg gratings for a variety of time-domain-based pulse shaping and processing applications. Such applications include dispersion compensation, square-pulse generation, pulse repetition-rate multiplication, and all-optical header generation and recognition for packet-switched all-optical systems.

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