Data storage in optical fibers and reconstruction by use of low-coherence spectral interferometry

Shay Keren, Erel Brand, Yoav Levi, Boris Levit, and Moshe Horowitz

Department of Electrical Engineering, Technion—Israel Institute of Technology, Haifa, 32000 Israel

Received August 20, 2001

We demonstrate optical data storage in optical fibers and reconstruction by use of low-coherence spectral interferometry. The information was stored by means of writing fiber Bragg gratings with different central wavelengths at different locations of the fiber. We need only a single short pulse is needed to read all the stored data. The maximum theoretical reconstruction rate that can be obtained with our technique is 10 Tbits/s. Our storage technique can be useful for identifying users in optical communication networks.

OCIS codes: 210.0210, 060.2340, 050.2770.

Optical information stored in fibers by writing an array of fiber Bragg gratings has been used in optical communication networks as a security code for identifying users as well as for optical code-division multiple access.[1–3] Previously, the information was stored in the fiber by means of writing several Bragg gratings at different locations with different central wavelengths or with different reflection coefficients. Optical information has also been stored by writing dynamic gratings based on spatial hole burning in erbium-doped fiber amplifiers.[4] After the fiber Bragg grating or the dynamic grating array was written, the stored information was read by means of sending a short pulse into the multiple-grating structure and measuring the temporal response of the reflected wave.[1–4] This reconstruction technique requires the use of expensive sources that generate short pulses. Moreover, because of the limited response time of the detection, the spatial separation between different gratings must be greater than some minimum length, and therefore the readout time and the amount of information that could be stored per unit length of the fiber were limited. The storage capacity was also limited, since only a single grating was written in each location of the fiber.

In this Letter we present a novel technique for reading information stored in an optical fiber by use of low-coherence interferometry performed in the frequency domain.[5] Unlike reconstruction techniques based on low-coherence inteferometry performed in the time domain, which require a slow mechanical scan,[6] our technique needs only a single short pulse to read all the stored information. With a light source with a bandwidth of ~70 nm, we can separate reflections with a time resolution of the order of 100 fs, while the pulse duration can be of the order of a nanosecond. We store the information by writing several gratings with different wavelengths at the same location and (or) at different locations along the fiber. Since several gratings are written at the same location, a maximum storage capacity per unit length of the fiber of 10^4 bits/cm can theoretically be obtained. The maximum fiber length that can be used in our system is ~5 cm because of the limited resolution of the spectrum analyzer. Since all the stored data can be read with a single pulse, the theoretical data reconstruction rate can be as high as 10 Tbits/s. The stored data are simply retrieved from the measured spectrum by use of the Gabor transform. We demonstrate our technique experimentally by writing as many as 260 Bragg gratings in a fiber.

A schematic of our system is shown in Fig. 1. A binary code with N bits is stored by as many as N gratings. Each 1 bit in the code is represented by a different grating. The gratings are stored in l different locations, and the central wavelength of each grating is one of $m = N/l$ different wavelengths. There is no spatial overlap of gratings written in different locations, and there is also no significant spectral overlap of gratings that have different central wavelengths. The stored information is read by use of low-coherence spectral interferometry. The output of a low-coherence laser source is split by a 3-dB coupler to form a Michelson interferometer. A mirror is connected to one output of the coupler, while the multiple-grating structure is connected to the other output. The interference spectrum is measured with a spectrum analyzer. A Fourier transform performed on the interference spectrum gives the impulse response of a grating.[5] To obtain both the location and the central

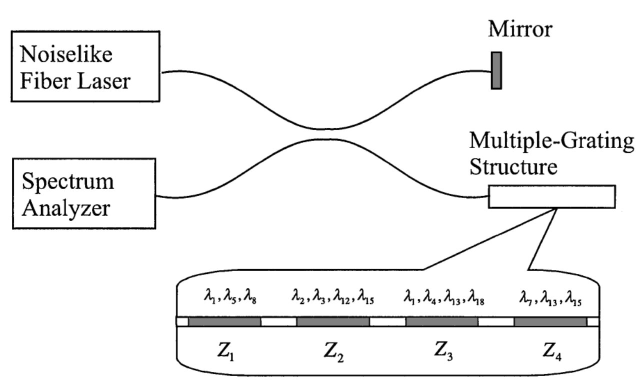

Fig. 1. Schematic of the experimental setup and the multiple-grating structure written in the fiber.

reflection wavelength of each grating in the structure, we use a combined time–frequency Gabor transform. The Gabor transform is defined as[7]

$$G(t, \Omega) = \int_{-\infty}^{\infty} I(\omega) W(\omega - \Omega) \exp(-i\omega t) \mathrm{d}\omega\,, \qquad (1)$$

where $I(\omega)$ is the interference spectrum and $W(\omega - \Omega)$ is a window function centered at frequency $\omega = \Omega$. The Gabor transform gives the response of the grating to pulses with a spectrum W centered at different optical frequencies Ω.

The theoretical data storage capacity is $N = lm = (L/d)(\Delta\lambda/\Delta\lambda_g)$, where d and $\Delta\lambda_g$ are the length and the bandwidth of a single grating, L is the fiber length, and $\Delta\lambda$ is the bandwidth of the light source. The maximum fiber length that can be read with low-coherence spectral inteferometry technique is limited by the resolution of the spectrum analyzer, $\delta\lambda$. Assuming a spectrum analyzer with a Gaussian line shape, the maximum length equals $L = 2\ln(2)\lambda^2/\pi n\delta\lambda$, where λ is the wavelength and n is the refractive index. The bandwidth of a uniform Bragg grating with low reflectivity, defined as the bandwidth between the first zeros of the reflection spectrum, equals $\Delta\lambda_g = \lambda^2/nd$.[8] Therefore, the theoretical storage capacity equals $N = nL/\lambda$, assuming that the entire bandwidth, c/λ, is used. Since a fiber is essentially a one-dimensional element, this result is in accordance with the theoretical storage capacity of three-dimensional holographic storage, $(nL/\lambda)^3$.

Using a spectrum analyzer with a spectral resolution of $\delta\lambda = 0.015$ nm, we find that the maximum fiber length is ~4.8 cm. Assuming that the shortest central wavelength of the grating, λ, equals 1.55 μm, the theoretical storage capacity is 45 kbits, and the number of different combinations that can be generated for a security code is $2^{45,000}$. The recovery time of the data is determined by the round-trip propagation time through the multiple-grating structure and by the minimum response time of the spectrum analyzer. Assuming that the spectrum analyzer is implemented by a diffraction grating and an array of detectors, the minimum response time is determined by the duration of the optical signal at each detector. For a spectrum analyzer with a Gaussian transfer function with a full width at half-maximum (FWHM) $\delta\lambda = 0.015$ nm, the minimum FWHM of the signal duration at each detector equals $\Delta t = 4\ln(2)\lambda^2/\pi c\delta\lambda = 470$ ps. Therefore, the stored information can be read at a maximum reconstruction rate of $R = N/\Delta t = 10$ Tbits/s.

We demonstrated experimentally the storage of binary data in an optical fiber by use of fiber Bragg gratings and reconstruction of the data by low-coherence spectral interferometry (see Fig. 1). Our light source was a fiber laser that operates in the noiselike mode of operation[9,10] and generates pulses with a repetition rate of ~10 MHz and with a broad spectral width of up to 70 nm. The average output power was 60 mW, and the pulse width was as short as 100 ps. The central wavelength of the laser was ~1.55 μm, and it could be continuously tuned over more than 20 nm by adjustment of the intracavity polarization controllers. We stored the information by writing uniform gratings with a length of ~1 mm. The spatial distance between adjacent gratings was 2.5 mm. The gratings were written in hydrogen-loaded optical fiber that was exposed to ultraviolet light, $\Lambda = 244$ nm, through a phase mask. We used as many as 20 different phase masks with central wavelengths in the wavelength regime 1538–1558 nm. The central wavelength of the gratings could be changed with a step size of 1 nm. We chose the reflectivity of each grating to be small (2%) to decrease the effect of multiple reflections between gratings with the same central wavelength. The relatively weak reflection coefficient of the gratings also minimized the attenuation of the wave as it propagated through the multiple-grating structure. The resolution of our spectrum analyzer, 0.015 nm, allowed us to read the information stored in a fiber section as long as 4.8 cm. Therefore, we could store as many as 260 bits, and the number of different combinations that could be generated for a security code was 2^{260}. The spectrum analyzer used in our experiment was based on a slow mechanical scan that did not allow us to demonstrate the high theoretical reconstruction rate of our system. We intend to replace the spectrum analyzer with a real-time spectrum analyzer based on a diffraction grating and a detector array. With a real-time spectrum analyzer, the data reconstruction rate can theoretically be as high as 550 Gbits/s.

Figure 2 shows a measured interference spectrum, normalized by the spectrum of our laser source. To reconstruct the data from the interference spectrum, we used the Gabor transform with a Gaussian window function that had a FWHM of 0.4 nm. The spatial and the spectral resolution in the Gabor transform are inversely connected because of the uncertainty principle. Therefore, we chose the width of the window function to obtain the best resolution between gratings in the spectral as well as in the spatial domain. Since the data are stored in a binary format, we used a threshold to eliminate noise and to detect only strong reflections. The threshold was chosen to be 10% of the maximum intensity. Figure 3 shows the results for two different data codes that were stored in a fiber. To demonstrate the results visually, we stored data that form

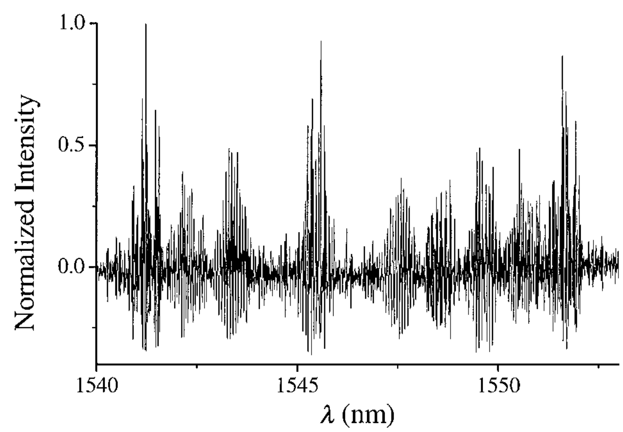

Fig. 2. Measured interference spectrum, normalized by the spectrum of the light source, used to reconstruct the information shown in Fig. 3.

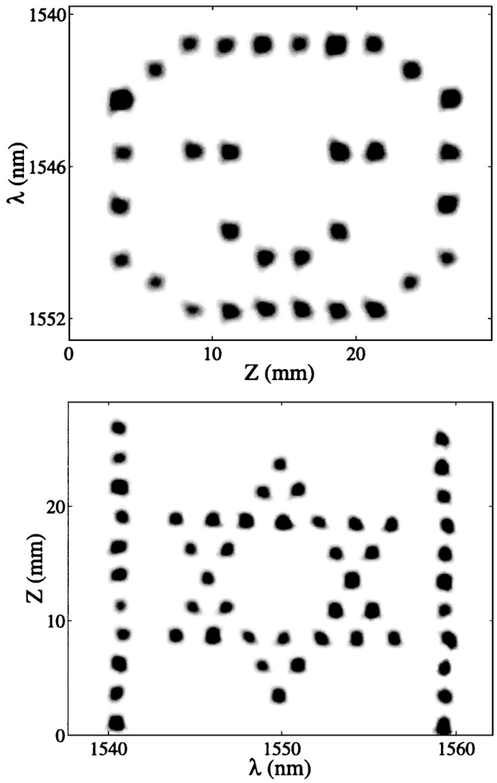

Fig. 3. Reconstructed data measured for two different data codes stored in the fiber. The black regions represent the points in the Gabor transform that have an intensity above a threshold as a function of the wavelength, λ, and the location along the fiber, z.

a meaningful picture in the frequency-spatial coordinates. The black regions in the figure represent the regions in the Gabor transform that have an intensity above the threshold as a function of wavelength, $\lambda = 2\pi c/\omega$, and location, $z = tc/2n$. The results show that we can clearly distinguish between different gratings with a good signal-to-noise ratio. Since the data are shown after performance of a threshold operation, the decay of the reflected intensity as a function of distance z cannot be observed in Fig. 3. This effect is due to a decrease in the transmitted intensity along the multiple-grating structure that is caused by the reflection of the gratings located close to the input end of the structure. The decrease in the reflected intensity can be overcome by an increase in the reflectivity of the gratings located close to the output end of the grating structure or by use of a detection algorithm that takes the decay of the intensity with distance into account, as was done in Fig. 3.

In conclusion, we have demonstrated optical data storage in fibers by use of fiber Bragg gratings and reconstruction of the data by low-coherence spectral interferometry. As much as 45 kbits can theoretically be read with a single pulse. The stored information can be reconstructed with a theoretical reconstruction rate of 10 Tbits/s. Our storage technique can be used in optical communication networks for coding, for identifying users, and for realization of an optical key.

We thank A. Bekker and V. Goloborodke for helping us to write the gratings. This work was supported by the Division for Research Funds of the Israeli Ministry of Science. S. Keren's e-mail address is eeshay@tx.technion.ac.il.

References

1. L. R. Chen, S. D. Benjamin, P. W. E. Smith, J. E. Sipe, and S. Juma, Opt. Lett. **22,** 402 (1997).
2. G. E. Town, K. Chan, and G. Yoffe, IEEE J. Sel. Top. Quantum Electron. **5,** 1325 (1999).
3. D. B. Hunter and R. A. Minasian, Electron. Lett. **35,** 412 (1999).
4. J. S. Wey, D. L. Butler, N. W. Rush, G. L. Burdge, and J. Goldhar, Opt. Lett. **22,** 1757 (1997).
5. S. Keren and M. Horowitz, Opt. Lett. **26,** 328 (2001).
6. S. R. Chinn and E. A. Swanson, Opt. Mem. Neural Netw. **5,** 197 (1996).
7. D. Gabor, J. Inst. Electr. Eng. Part 3 **93,** 429 (1946).
8. T. Erdogan, J. Lightwave Technol. **15,** 1277 (1997).
9. M. Horowitz, Y. Barad, and Y. Silberberg, Opt. Lett. **22,** 799 (1997).
10. M. L. Dennis, M. A. Putnam, J. U. Kang, T. E. Tsai, I. N. Duling, and E. J. Friebele, Opt. Lett. **22,** 1362 (1997).