

Video Article

Quasi-light Storage for Optical Data Packets

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Abstract

Today's telecommunication is based on optical packets which transmit the information in optical fiber networks around the world. Currently, the processing of the signals is done in the electrical domain. Direct storage in the optical domain would avoid the transfer of the packets to the electrical and back to the optical domain in every network node and, therefore, increase the speed and possibly reduce the energy consumption of telecommunications. However, light consists of photons which propagate with the speed of light in vacuum. Thus, the storage of light is a big challenge. There exist some methods to slow down the speed of the light, or to store it in excitations of a medium. However, these methods cannot be used for the storage of optical data packets used in telecommunications networks. Here we show how the time-frequency-coherence, which holds for every signal and therefore for optical packets as well, can be exploited to build an optical memory. We will review the background and show in detail and through examples, how a frequency comb can be used for the copying of an optical packet which enters the memory. One of these time domain copies is then extracted from the memory by a time domain switch. We will show this method for intensity as well as for phase modulated signals.

Video Link

The video component of this article can be found at <https://www.jove.com/video/50468/>

Introduction

The data transport in the telecommunications networks is optically, since only optical fibers offer the capacity required for today's data traffic transmitted around the world. However, in every node of the network the optical signal has to be transferred into the electrical domain in order to process it. After processing the signal is converted back to the optical domain for further transmission. This double-transfer between the domains is both time and power consuming. In order to use an all-optical processing of the data, the problem of the intermediate storage has to be solved. Thus, lots of methods for the storage or buffering of the optical signals have been suggested. The simplest way is to send the signals into a matrix of waveguides with different lengths². However, these matrices are bulky and the storage time cannot be tuned since it is predefined by the waveguide length.

The "Slow-Light" method relies on a tunable change of the group refractive index of a medium to slow down the propagation speed of optical signal pulses². Several physical effects and material systems can be used for this purpose³⁻⁶. However, with these methods the signal can be slowed down by just a few bit-lengths, which is by far not sufficient for optical network nodes^{7,8}.

Another approach uses wavelength conversion and dispersion for the generation of tunable delays. Thereby, the center wavelength of the input signal is shifted via nonlinear optical conversion. Afterwards, the signal is fed into a highly dispersive fiber. The difference in the group velocity in the dispersive fiber leads to a delay that is proportional to the product of the wavelength shift and the group-velocity dispersion (GVD) in the fiber. With a second conversion the wavelength is shifted back to the original value. For the wavelength shift techniques like four-wave mixing or self phase modulation can be used. With the conversion and dispersion method storage times up to 243 nsec of tunable delay, which correspond to 2,400 bit, were reported¹⁰. However, wavelength conversion and dispersion methods in general need special components and setups for producing a large wavelength shift and/or large GVD. Additionally, they are among the most complex and power-hungry delay methods².

Other methods store the optical signal into an excitation of a material system. A probe beam is then used to read out the information. Usually these systems cannot be used in the area of telecommunications since they require ultrahigh or -low temperatures¹¹, will not work with telecommunications bandwidths, or require rather complicated setups and high power¹²⁻¹⁴.

Here we show how a basic property of signals (the time-frequency coherence) can be exploited for the storage of optical data packets. Since no excitation of a material system is used, we have called the method Quasi-light Storage (QLS)¹⁵⁻¹⁷. The QLS is independent of the modulation, data format and data rate of the packets and can store optical packets for several thousand bit lengths¹⁸.

The basic idea can be seen in **Figure 1**, here rectangular shaped pulses are shown. However, the method works for every pulse shape and for packets of pulses. The only restriction is that the signals have to be time-limited.

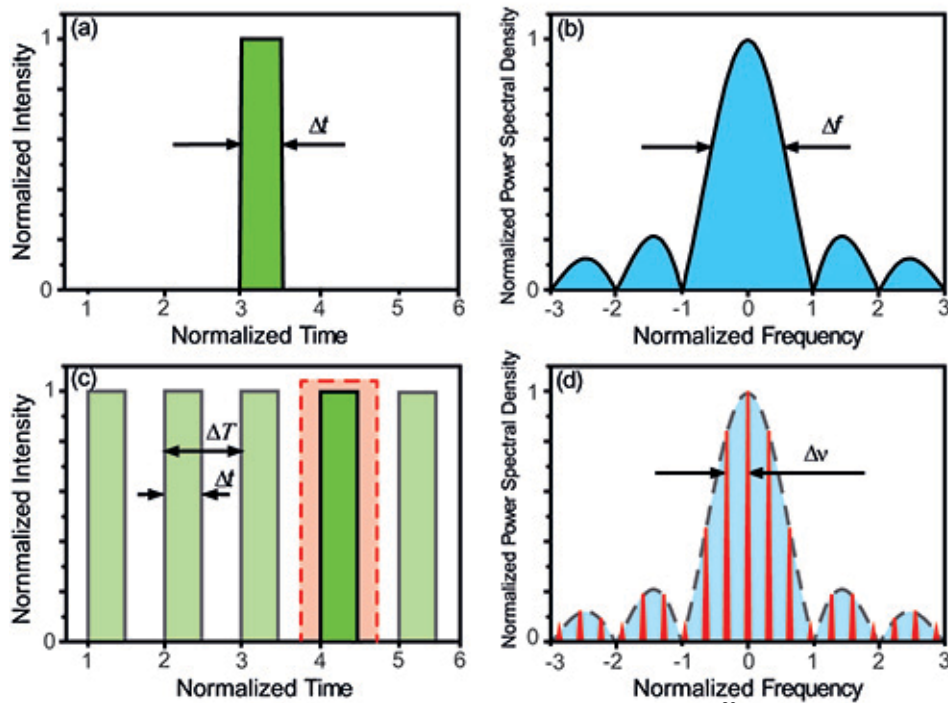


Figure 1. Time-frequency coherence for an intensity modulated signal²³. A single rectangular signal in the time domain (a) is represented by a sinc-function in the frequency-domain (b). Here the normalized intensity is shown, since it is not possible to measure the fields with optical equipment. The time domain representation for a sequence of rectangular signals is shown in (c). This sequence has still the same spectral shape. But, it consists of equidistant single frequencies under the sinc-envelope (d). The time axis are normalized to half the duration of a single signal and the frequency axis to the first zero crossings, respectively. [Click here to view larger image.](#)

A rectangular pulse in the time domain (**Figure 1a**) has a "sinus cardinalis" or sinc function $\sin(px) / px$ shaped spectrum (**Figure 1b**), where all frequencies under the envelope are present. A train of rectangular pulses in the time domain (**Figure 1c**) has still a sinc function shaped spectrum (**Figure 1d**) with the bandwidth Δf . But due to the periodicity, not all frequencies are present anymore. Instead, the spectrum consists of equidistant frequencies and the inverse of the frequency spacing defines the time separation between the pulses $\Delta T = 1/\Delta \nu$.

The basic idea of the QLS is now simply to extract equidistant frequencies out of the spectrum of the input packet. Due to time-frequency coherence this results in a copying of the packet in the time domain. The copy with the desired delay can be extracted by a time domain switch.

The principle of our experiment is shown in **Figure 2**. A time-limited input signal is multiplied with a frequency comb in the frequency-domain. For the multiplication the nonlinear effect of stimulated Brillouin scattering (SBS) is used. The results are equidistant copies of the input signal in the time-domain. One of the signals is extracted with a switch driven by a rectangular function. Thus, at the output of the memory in principle a distortion-free copy of the input pulse can be expected.

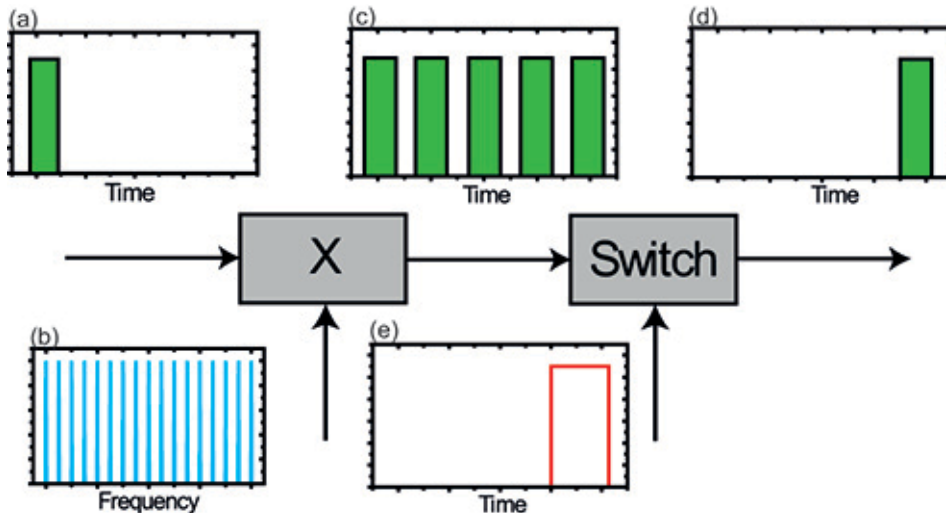


Figure 2. Basic idea of the Quasi-light Storage¹⁵. A time limited input signal (a) is multiplied with a frequency comb (b) in the frequency-domain, which is denoted with a X. This leads to various copies of the signal in the time domain (c). From the generated pulse train one of the copies (d) is extracted with a time-domain switch by a rectangular read signal (e). The switch can be a modulator. The result is a storage of the optical signal. The storage time is defined by the frequency spacing between the comb lines and the read signal. [Click here to view larger image.](#)

SBS itself is a nonlinear effect that can occur in standard single mode fibers (SSMF) at low powers. Thereby, the signal interacts with an optical density change which is generated by a counter propagating pump wave. If the signal wave is downshifted in frequency, a gain region is formed in which the signal will be amplified. If it is up-shifted the signal will be attenuated in the corresponding loss region. The frequency shift between pump and signal is defined by the acoustic wave, which depends on the material properties. The biggest advantage of SBS for the presented application is the narrow bandwidth Δf_{SBS} of the gain region. Thus, practically SBS forms a narrow linewidth optical filter. The narrow bandwidth of the gain region depends on the effective length and area of the fiber as well as on the used pump power¹⁹. The natural full-width at half-maximum (FWHM) bandwidth of the SBS gain in a SSMF is around 30 MHz. In special waveguides, such as AllWave fibers, and with high pump powers, the bandwidth can be reduced down to 10 MHz²⁰. Due to the filter bandwidth the different copies are covered with an envelope. Therefore, the maximum storage time of the QLS inversely depends on the SBS bandwidth. A bandwidth of 10 MHz would result in a maximum storage time of 100 nsec. [Click here to view larger image.](#)

For very high bit-rate transmission the information has to be encoded into the phase of the carrier instead of its amplitude, since this offers a lot of advantages. Thus, contrary to pulses, the signals in these optical networks have constant amplitude. **Figure 3** shows such a phase modulated signal in the time (left) and frequency domain (right). This spectrum can be sampled in the same way as that of the amplitude modulated signal²¹. In fact the spectrum of the rectangular function for intensity- and phase-modulated signals is filtered due to the transmission, which limits the spectrum.

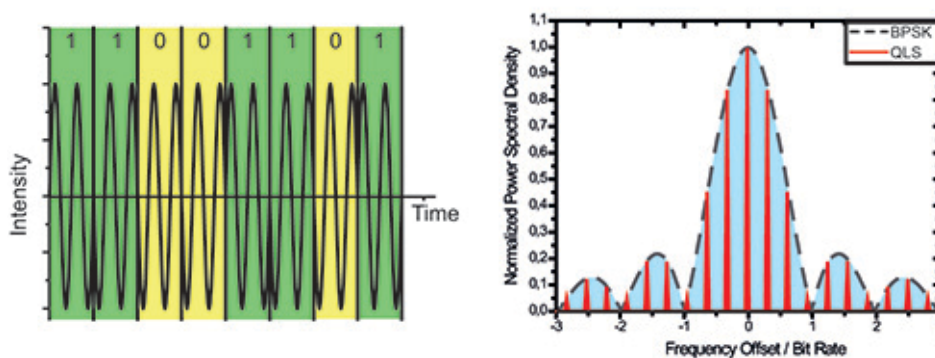


Figure 3. Time-frequency coherence for a phase modulation²¹. In a phase modulated signal the phase of the carrier is changed by the signal which has to be transmitted. If each symbol consists of 1 bit, the phase is changed between 0 and π , for instance. The left side of the figure shows the resulting time-domain representation for such a binary phase shift keyed (BPSK) signal. The resulting frequency-domain signal is shown on the right side. By comparison with **Figure 1** it can be seen that the spectrum of the phase modulated signal is qualitatively the same as that of the intensity modulated signal. Thus, the QLS can be applied in the same way.

Protocol

1. Preparing the System (Figure 4)

1. Insert the laser diodes LD1 and LD2 in the specific mount and connect it with the current (LDC) and temperature controllers (TEC). Turn the devices on and check the functionality of the laser diodes with the optical spectrum analyzer. Usually, a telecom wavelength around 1,550 nm is used.
2. Connect the laser diode to the modulators (IM/PM and MZM1) according to the setup in **Figure 4**. The optical connectors need to be cleaned before use, to ensure the clean surface for coupling. Connect the power supply (not shown) and the signal from the waveform generator (AWG) with an additional electrical amplifier to the modulator. Ensure that the maximum optical and electrical input power at the modulator is not exceeded. Every Modulator is equipped with a polarization controller.

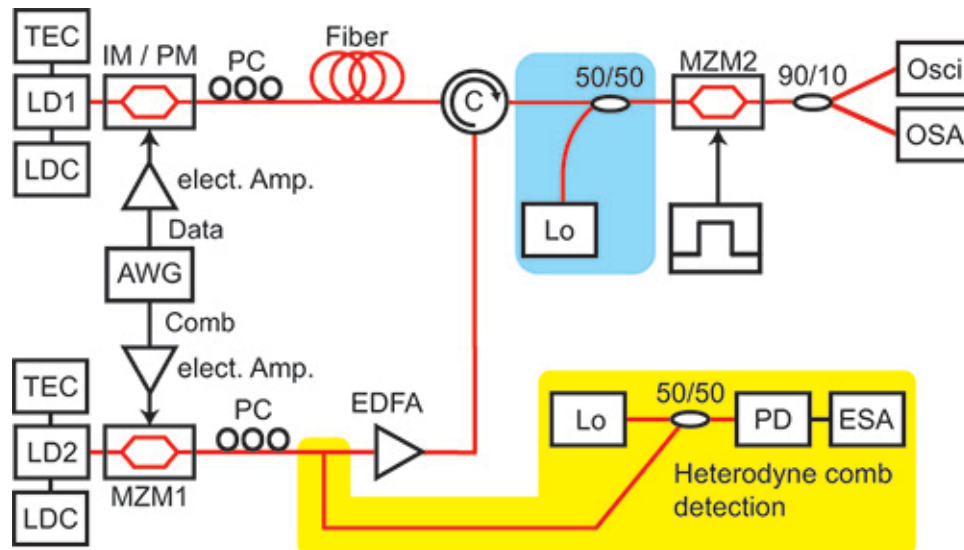


Figure 4. Experimental setup of the QLS whereby the storage of intensity and phase modulated signals is possible. The blue labeled section is only necessary for the detection of phase modulated signals. The QLS process takes place in the optical fiber. The yellow labeled section defines the heterodyne detection of the frequency comb. TEC: temperature controller, LDC: laser diode current source, LD: laser diode, IM: intensity modulator, PM: phase modulator, PC: polarization controller, AWG: arbitrary waveform generator, MZM: Mach-Zehnder modulator, EDFA: erbium doped fiber amplifier, C: circulator, Lo: local oscillator, Osci: oscilloscope, OSA: optical spectrum analyzer, PD: photodiode, ESA: electrical spectrum analyzer. [Click here to view larger image.](#)

3. Connect the fiber with the modulator for the data signal. For phase modulated signals it has to be a phase modulator (PM) and for intensity modulated signals an intensity modulator (IM). Usually, the data rate for the experiment is in the Gbps range. The other side of the fiber is connected with port 2 of the circulator (C). The used AllWave fiber in our experiments has the following specifications: $L = 20$ km, $\Delta f_{\text{SSB}} = 10.2$ MHz, $f_{\text{SSB}} = 10.852$ GHz, $P_{\text{th}} \approx 9.1$ dBm.
4. Connect the amplitude modulator for the frequency comb generation (MZM1) with the optical amplifier (EDFA). The comb has to cover the bandwidth of the data signal. The output of the EDFA is connected with port 1 of the circulator.
5. For the detection of phase modulated signals, a reference source is needed. Connect the local oscillator (LO) together with the output 3 of the circulator to a 50/50 coupler. For intensity modulated signals, this part is not required. As LO a fiber laser (Koheras) is used.
6. For phase modulated signals: connect the third modulator (MZM2) for extracting the delayed copies with the output of the 50/50 coupler. For intensity modulated signals, connect MZM2 directly to port 3 of the circulator. Supply the modulator with a bias voltage (not shown) and a rectangular signal from the CH1 Mkr1 output port of the waveform generator for extracting. Therefore, the original data signals, as well as the rectangular signal for extracting are synchronized.
7. For detection and analysis: connect a 90/10 coupler after MZM2. The oscilloscope is connected with the 90% port of the coupler and the 10% part is connected with the optical spectrum analyzer.
8. Program the waveform generator with the required signals for the data packet, the frequency comb and the rectangular signal. The frequency comb is generated by a periodic sinc-function.

2. Measurement

1. Turn on the output for the data signal at the waveform generator (AWG). Change the bias for the modulator (IM/PM) at the power supply and control the signal quality at the oscilloscope. After adjusting the best quality turn the output of the waveform generator off. The modulators should be set around the linear operating point. Exemplary values can be found in the results section.
2. Adjust the quality of the frequency comb with heterodyne detection. An example for a relatively good quality frequency comb is shown in **Figure 5**. The frequency comb needs to be flat, e.g. all frequency components have the same intensity and are stable over time, as well as broad enough to cover the whole spectrum. Additionally, the edges of the comb should be steep, e.g. there are no apparent frequency components with a low intensity on the sides.

3. Heterodyne comb detection I: Connect the output of MZM1 with a 50/50 coupler. The other port of the coupler is connected with a fiber laser (Koheras) as local oscillator.
4. Heterodyne comb detection II: Due to the limited bandwidth of the photo-diode and the electrical spectrum analyzer, first the coupler output has to be connected to the optical spectrum analyzer in order to set the distance between the local oscillator and the signal to around 8 GHz by changing the temperature of the laser.
5. Heterodyne comb detection III: After the adjustment remove the optical spectrum analyzer and connect the photodiode and the electrical spectrum analyzer to the output of the 50/50 coupler. Adjust the bias voltage of the comb modulator to achieve a flat frequency comb. After completion connect the output of the modulator again to the optical amplifier (EDFA).
6. Adjust the distance between both laser diodes (IM/PM and MZM1) regarding the Brillouin shift with continuous wave signals. Thus, be sure that the output of the waveform generator is turned off.
7. Turn on the optical amplifier. Have a look at the optical spectrum analyzer and set the output power of the EDFA to a value below the threshold of stimulated Brillouin scattering.
8. Now shift the wavelength of the laser diode which generates the data signal (IM/PM) into the gain region of the pump (MZM1). The signal will be amplified if the wavelength is correct.
9. For optimization change the polarization of the data signal and therefore the intensity to the maximum.
10. Turn on both outputs (data signal and comb) of the waveform generator. Increase the output power of the EDFA. Now the frequency comb will extract equidistant components out of the spectrum. The oscilloscope should show the different copies generated by the QLS. For distortion reduction slightly shift the wavelength of the data signal and change the polarization.
11. To extract one of the copies use one of the marker signals of the waveform generator or an external source that can produce a rectangular pulse. Set up a rectangular pulse with the length of the packet.
12. Turn on the bias for MZM2 and change it to the operating point where the extracted signal is maximized and all other copies are suppressed. Now shift the rectangular pulse to the desired version of the stored pattern.
13. The stored data pattern can be saved with the oscilloscope and evaluated with software, e.g. Origin.
14. In order to switch between the measurement of intensity and phase modulated signals, the modulator for the data signal needs to be changed from IM for intensity modulated signals to PM for phase modulated signals. Additionally, for the phase modulated signals a local oscillator as a reference source needs to be added to the setup according to **Figure 4**.

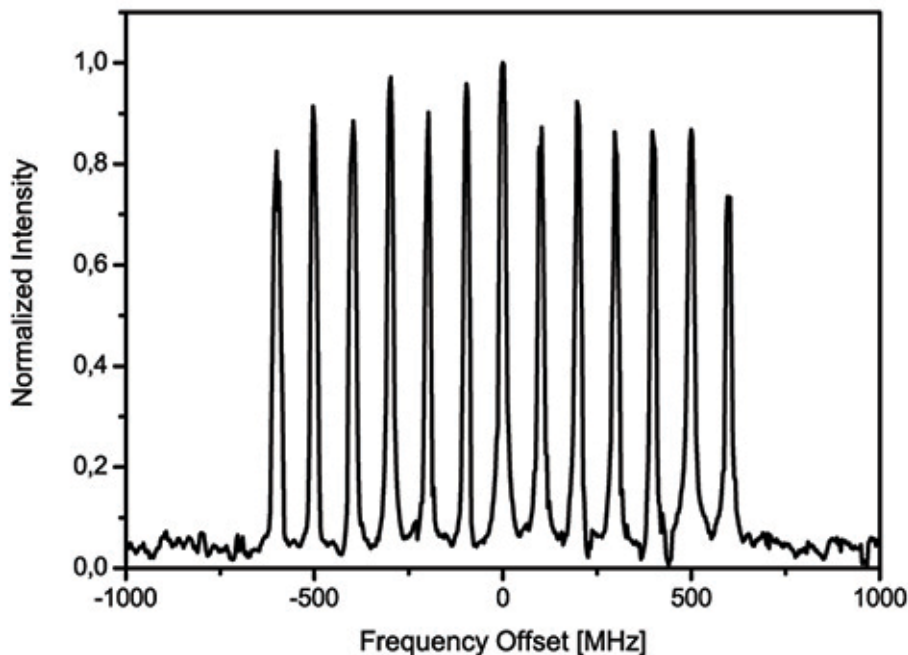


Figure 5. Almost flat frequency comb with 13 branches. The comb was detected via heterodyne detection. For the detection a local oscillator was combined via a 3 dB coupler with the optical signal and detected with a photodiode. The frequency comb was measured and recorded with an electrical spectrum analyzer. The output power of the local oscillator was 6 dBm and the optical power of the comb 8 dBm. The distance between the local oscillator and the optical comb was 9.8 GHz. For a better overview the frequency axis is normalized to the center frequency of the comb which was around 193.5 THz (1,550 nm). [Click here to view larger image.](#)

Representative Results

For the measurement a 10110101 intensity modulated data pattern with a data rate of 1 Gbps was used. The black line in **Figure 6** represents the original signal and the colored lines represent the different storage times achieved with the QLS. The reference is measured without the QLS and the deactivated switch at the output. Under ideal conditions storage times up to 100 nsec are achievable. The results for the stored 11001101 data pattern of a phase modulated signal, again with a data rate of 1 Gbps can be seen in **Figure 7**, with the reference signal on the left side (black) and the different extracted copies of the SBS based QLS. The stored versions of the original signal are almost distortion

free. This means that there are only small changes in the amplitude of the bits in the packet as well as just a slight pulse broadening. The measurement of the distortions is carried out qualitative for each packet by measuring the specific values with the oscilloscope.

The quality and amount of copies depends on the pump power, the flatness of the comb and the polarization. If the frequency comb is not flat enough, distortions in the pattern and the different copies occur. If the pump power is too low there will be a less amount of copies, since the power for every single line in the comb will decrease. In the case of low pump power the SBS gain bandwidth will be broader and therefore the maximum storage time decreases. Additionally, if the pump power is too low, there is no SBS gain and no filtering. As can be seen, the maximum storage time in **Figure 7** is 60 nsec. Due to the limitations of the equipment, the pump power during the measurement was too low. Therefore the Brillouin gain bandwidth could not be reduced to its minimum and the maximum storage time is limited to 60 nsec.

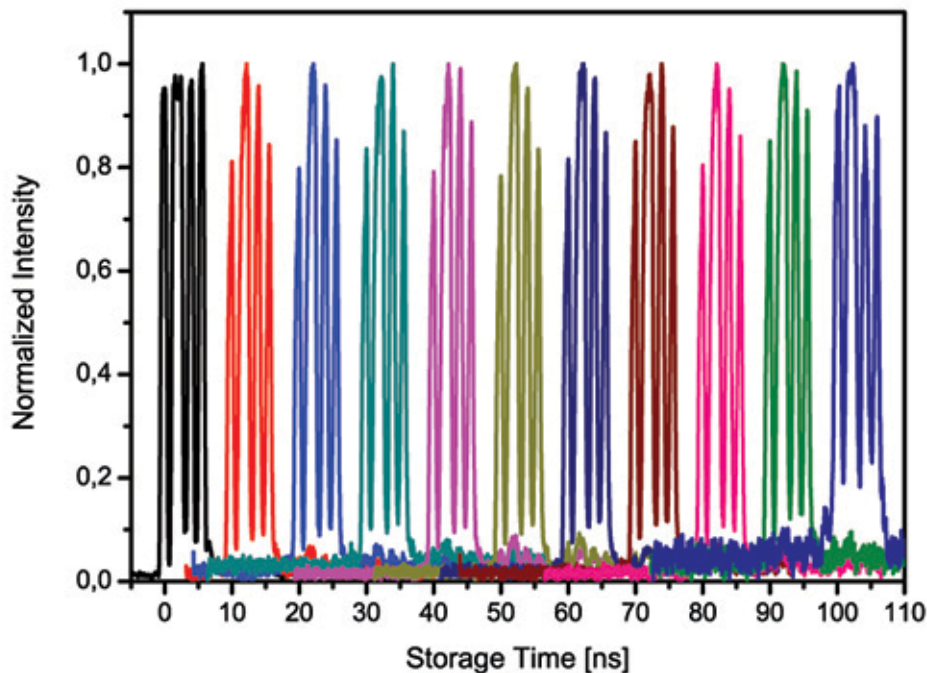


Figure 6. Quasi light storage of an intensity modulated signal¹⁷. Within the figure the measurement results for an intensity modulated signal with the bit sequence 10110101 can be seen. The copies generated by the QLS are shown in addition to the reference signal on the left (black). The used frequency comb was generated with the AWG and a MZM. The RF input power of the MZM was 20 dBm and the bias voltage 3.76 V. Within the experiment the output power of the EDFA for the comb was 26 dBm. The data signal was generated by the AWG and another modulator, as well. The data RF input power to the modulator was 24 dBm and the bias voltage 1.54 V. The optical power of the data signal was 6 dBm. As Brillouin medium a 20 km AllWave fiber was used. The QLS generate different copies of the original signal. Every copy was extracted separately with a MZM driven by a rectangular signal. The RF input power was 4 dBm and the bias voltage was 2.57 V. The measurement of the data signal, as well as the copies was done with an oscilloscope with an optical input. The xy data of the extracted copies was saved and analyzed. [Click here to view larger image.](#)

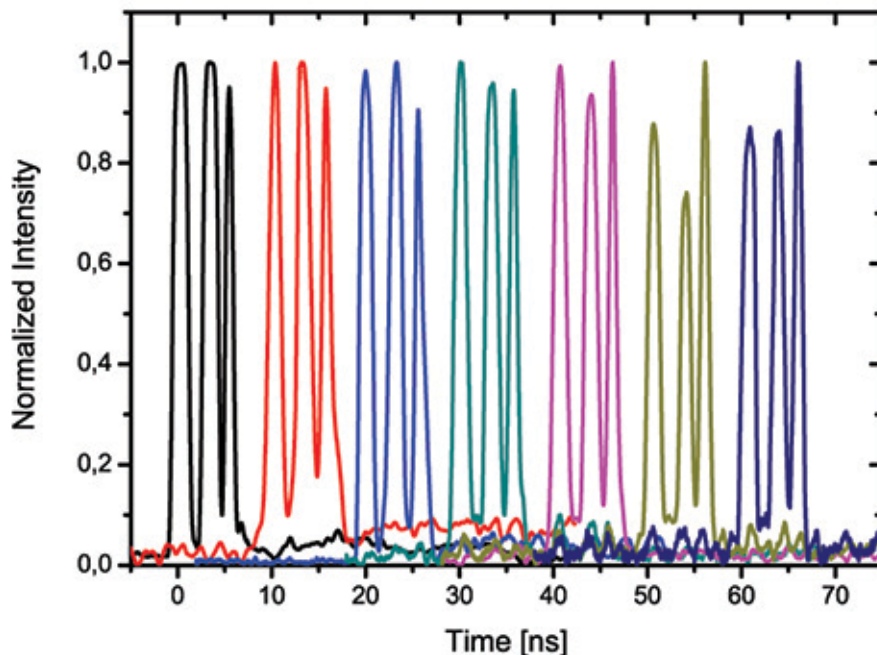


Figure 7. Quasi light storage of a phase modulated signal²¹. The black line on the left side shows the original 11001101 data pattern. The colored lines show the different extracted copies which are generated via QLS. The used frequency comb was generated with a sinc function out of the AWG and a MZM. The MZM was driven at 20 dBm RF input power and a bias voltage of 3.76 V. The data signal is generated from the AWG as well, and transferred into the optical domain with a phase modulator driven with an RF power of 19 dBm. As Brillouin medium a 20 km AllWave fiber was used. The output power of the EDFA for the comb was 23 dBm. The optical power of the data signal before the fiber was 10 dBm. The copies generated via QLS are extracted with an MZM and a rectangular signal out of the AWG. The RF input power was 4 dBm and the bias voltage was 3.5 V. To detect the copies with the oscilloscope the signal is combined with a local oscillator to get a reference phase, as explained in the procedure part. The signal was measured and recorded with the oscilloscope and evaluated with Origin. [Click here to view larger image.](#)

Discussion

The most critical step during the experiment is the adjustment of the frequency comb, *i.e.* the bandwidth, flatness and position in respect to the data signal in the frequency domain. According to the sampling theorem in frequency domain, signal distortions are avoided if the whole bandwidth of the optical packet is sampled with an ideally flat comb. Thus, the bandwidth of the optical packet defines the minimum bandwidth of the frequency comb and in this bandwidth the comb has to be as flat as possible. A nonideal frequency comb will lead to an irregular multiplication with the data spectrum and therefore to an uneven sampled spectrum. This would increase the distortions significantly. The same effect occurs when the position of the gain comb and the data spectrum does not fit correctly. If just half of the gain comb is within the data spectrum, for instance, the result would be an uneven sampled spectrum and the distortions would be increased.

The method itself is limited by two factors: the packet length and the bandwidth of stimulated Brillouin scattering. The natural full width at half maximum (FWHM) bandwidth of the SBS is around 30 MHz. In special waveguides, such as AllWave fibers, and with high pump powers, the bandwidth can be reduced down to 10 MHz. This results in a maximum storage time of 100 nsec. Additionally, the length of one packet is limited to the distance between the copies. If it would exceed this distance, the copies would be distorted. To overcome this limitation the distance of the branches in the frequency comb can be reduced and therefore the distance of the copies in the time domain will be enhanced.

The overall storage time directly depends on the Brillouin gain bandwidth. Therefore, by reducing the bandwidth the storage time can be increased significantly. This can be done by the superposition of the gain with two losses¹⁷ as well as using a multi stage Brillouin system²². These modifications are easy to implement but enhance the complexity of the system, respectively. Additionally, the storage time can be enhanced by using a loop around the system. Therefore the extracted packet is fed back into the system after each round trip.

The outstanding advantages of this method are the tunable, high storage time as well as the independence of the modulation format and the rather simple setup. Other comparable all optical storage methods are limited to storage times of just a few bits, like the slow light approach⁸, or have a fixed storage time, *e.g.* in a loop matrix.

The required components for the QLS are commercially available and can be integrated easily. As slow light medium the transmission fiber itself can be used. Therefore network nodes could be easily equipped with the QLS technique. The only component that is needed in addition is a central control logic which controls the storage times.

Disclosures

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