Then the total field reflected from the array is $E^T = E^* + E^t$ and we can define a total reflection coefficient as $R^T = \frac{E^t}{E^*}$. The moment method analysis techniques of References 6-8 can be used to find $\vec{S}$. The only substantial difference from that work is the use of the equivalence theorem to express the voltage vector elements in terms of $J$, an equivalent surface current that produces $E^* + E^t$ in the presence of the substrate [6]. It can be shown that

$$f = -\frac{2}{\eta_0} E_o e^{i\omega_0 t} \sin \left( \gamma x + \phi_0 \right)$$

where $E_o = \sqrt{2} E_{\omega_0} \cos \omega_0 \sin \phi_0 + j E_{\omega_0} \sin \phi_0$. Then $\vec{V}_i$ can be simplified to

$$\vec{V}_i = \frac{-2}{\eta} E_o \vec{\vec{g}}(k_{\omega_0}, k_{\omega_2}) F \vec{\vec{h}}(k_{\omega_0}, k_{\omega_2}) \exp[\text{inc} \eta_0]$$

where $k_{\omega_0} = -k_{\omega_2}$, $k_2 = -k_{\omega_0}$ and $F_i$ is the Fourier transform of the ith expansion mode. Note that if $E_o$, $E_{\omega_0}$, $\omega_0$, $\phi_0$, and $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$. Then $\vec{V}_i$ can be simplified to

$$\vec{V}_i = \frac{-2}{\eta} E_o \vec{\vec{g}}(k_{\omega_0}, k_{\omega_2}) \cdot \vec{\vec{F}} \vec{\vec{h}}(k_{\omega_0}, k_{\omega_2}) \exp[\text{inc} \eta_0]$$

Data were also calculated for a similar reflectarray using a rectangular array grid, with the result that the phase curves were very similar to those in Fig. 2. This indicates that the spacing and layout of the array grid is not very important, as long as grating lobes are not generated for the desired scan angle. It also implies that mutual coupling effects are not critical to this application of microstrip patches.

References


MULTIGIGABIT/s PULSE SOURCE BASED ON THE SWITCHING OF AN OPTICAL BEAT SIGNAL IN A NONLINEAR FIBRE LOOP MIRROR

S. V. Chernikov and J. R. Taylor

Indexing term: Fibre optics

A novel technique for the generation of a high repetition rate train of transform-limited pulses is demonstrated. A 32 GHz train of 4 ps pulses has been generated.

The use of a dual frequency optical beat signal for generation of pulse trains in the gigahertz repetition rate range has been recently proposed and experimentally demonstrated [1-5]. The key idea of this approach is to reshape the half periods of the sinusoidal beat signal into well separated pulses. The reshaping can be achieved using nonlinear propagation in an optical fibre influenced by "slow" amplification or dispersion decreasing along the fibre length [1-4]. Or, alternatively, by exploiting the soliton Raman self-scattering effect [5].

We present a novel technique for pulse train generation through optical beating based on the use of a nonlinear fibre loop mirror (NFLM). The NFLM has recently been paid considerable attention as a fast optical switch for optical signal processing [6-9], for optical pulse shaping [10] and in passively modelocked fibre lasers [11-12]. Here, we demonstrate theoretically and experimentally how the nonlinear switching characteristics of the NFLM in conjunction with a dispersion delay line can provide a mechanism for the transformation of a beat signal into a train of well separated transform-limited pulses at multigigabit/s repetition rates.

The principle of the operation is illustrated by Fig. 1. The powerful beat signal is generated by a dual frequency light source and directed into the NFLM. The NFLM consists of a 3dB coupler, an optical fibre, an optical attenuator (or

Fig. 1 Schematic diagram of experimental arrangement

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658
amplifier) (OA) situated close to one of the ends of the loop and a polarization controller (PC). The operation of such a loop (called a nonlinear amplified loop mirror for the case of using in line fibre amplifier) has been described in Reference 7. When an optical dual frequency beat signal \( E_{\text{in}}(t) \) is coupled into the loop, the electric field of the light transmitted through the loop is given by

\[
E_{\text{out}}(t) = \sqrt{E_{\text{in}}(t)} \exp(i\phi(t)) \exp(-i\omega L/c)
\]

\[
\phi(t) = \exp(ib_{\text{NL}}\cos^2(\pi L/t_0)\exp(-i\omega L/c))
\]

where \( E_p \) is the field amplitude, \( \omega_0 \) the mean frequency, \( t_0 \) the beat period, \( L \) the loop length and \( \delta = (1 + 6\pi N_2/|E_p|^2 L/(2c))^2 \) is the amplitude of the nonlinear phase shift generated due to the self-phase modulation effect (SPM). \( \delta = (1 - 6\pi N_2/|E_p|^2 L/c) \) is the nonlinear phase shift between clockwise and counterclockwise propagating waves. The phase bias \( \Delta \phi \) is achieved by putting an optical attenuator with loss coefficient \( T \) inside the loop next to the coupler. \( N_2 \) is the nonlinear refractive index.

\[ b_{\text{NL}} = \frac{W}{15L} - T \]

\[ A(t) = \sin(0.5 \Delta \phi \cos^2(\pi t/t_0)) \]

\[ \phi(t) = \exp(ib_{\text{NL}}\cos^2(\pi t/t_0)) \]

The phase bias \( \Delta \phi \) is achieved by putting an optical attenuator with loss coefficient \( T \) inside the loop next to the coupler. \( N_2 \) is the nonlinear refractive index.

The influence of the NFLM on the beat signal contributes to nonlinear amplitude shaping described by the function \( A(t) \) and phase modulation \( \phi(t) \). The nonlinear amplitude transmission characteristic for \( 0 < \Delta \phi < \pi \) provides a higher transmission for peaks of the sinusoidal envelope and relative suppression of the optical field around the minima. This leads to the transformation of the sinusoidal envelope into a train of separated pulses (see Fig. 2, curves a and b). The periodicity of the generated pulses is then determined by the input beat frequency. Additionally, the pulses exhibit a frequency modulation given by \( \phi(t) \). As the pulses transmitted by the NFLM are centred at \( t = t_0 \) (is an integer) and have duration considerably less than the period \( t_0 \) resulting from the amplitude shaping, the phase modulation over the pulses can be fairly well approximated by the expansion \( \phi_n = \phi_0 + \cos^2(\pi t_0/n_0) + \phi_1 + (\pi t_0/n_0) + O(t_0^2/n_0) \). This means that the frequency chirp \( \Delta \phi \) is almost linear over the pulses forming the train provided that \( \phi_0 \) is not too large (\( \phi_0 < 1.2n \)). Such linear chirp can be compensated for in an external delay line with a negative group velocity dispersion leading to further pulse compression (Fig. 2, curve c). The dispersion of the delay line was chosen to minimise the pulse width. The insert in Fig. 2 illustrates that the phase variation over the compressed pulse envelope is negligibly small, indicating that the pulses are effectively transform limited. In practice, the chirp compensation can be achieved with a dispersion delay line based on a pair of diffraction gratings (13) or using a piece of fibre in the anomalous group velocity dispersion spectral region.

The nonlinear phase shift as determined by eqn. 1 depends only on the beat signal power coupled into the loop and does not depend on the beat frequency. Therefore, this technique permits tuning of the repetition rate of the generated pulse train by varying the input beat frequency and optimising the dispersion chirp compensator (grating separation or fibre length) for every chosen repetition rate. However, the maximum repetition rate can be limited by the value of the fibre dispersion inside the loop because the phase matching condition for SPM requires that \( |\Delta v| < 4\omega_0 N_2/|E_p|^2 L/c \).

For the experimental demonstration of the technique, we used two single-frequency DFB laser diodes operating at 1532 nm as sources of the beat signal, followed by the amplification in an Er3+ doped fibre amplifier (EDFA) (Fig. 1). A Ti : sapphire laser operating at 970 nm was used to pump the EDFA. A 4-km dispersion shifted fibre and tunable optical attenuator (OA) were used in the NFLM. The light reflected by the loop was blocked by an optical isolator (I). A grating pair was employed as a delay line with variable negative second-order dispersion. The autocorrelation function and spectrum of a 32-GHz train of the transform-limited pulses generated are shown in Fig. 3. The pulse duration achieved (4.3 ps) corresponds to a mark space ratio as high as 1:7.5.

Diagram 2: Results of theoretical analysis

Curve a is the input beat signal intensity, b is the pulse shape transmitted by the NFLM and c is the final pulse train after compression in an optimised external delay line. The inset illustrates the phase variation over the generated pulse shown by dashed line. The amplitude of the phase shift \( \phi(t) \) and phase bias \( \Delta \phi \) used in the calculations are 1:4 and \( \pi/2 \), respectively.

The influence of the NFLM on the beat signal contributes to nonlinear amplitude shaping described by the function \( A(t) \) and phase modulation \( \phi(t) \). The nonlinear amplitude transmission characteristic for \( 0 < \Delta \phi < \pi \) provides a higher transmission for peaks of the sinusoidal envelope and relative suppression of the optical field around the minima. This leads to the transformation of the sinusoidal envelope into a train of separated pulses (Fig. 2, curves a and b). The periodicity of the generated pulses is then determined by the input beat frequency. Additionally, the pulses exhibit a frequency modulation given by \( \phi(t) \). As the pulses transmitted by the NFLM are centred at \( t = t_0 \) (is an integer) and have duration considerably less than the period \( t_0 \) resulting from the amplitude shaping, the phase modulation over the pulses can be fairly well approximated by the expansion \( \phi_n = \phi_0 + \cos^2(\pi t_0/n_0) \). This means that the frequency chirp \( \Delta \phi \) is almost linear over the pulses forming the train provided that \( \phi_0 \) is not too large (\( \phi_0 < 1.2n \)). Such linear chirp can be compensated for in an external delay line with a negative group velocity dispersion leading to further pulse compression (Fig. 2, curve c). The dispersion of the delay line was chosen to minimise the pulse width. The insert in Fig. 2 illustrates that the phase variation over the compressed pulse envelope is negligibly small, indicating that the pulses are effectively transform limited. In practice, the chirp compensation can be achieved with a dispersion delay line based on a pair of diffraction gratings (13) or using a piece of fibre in the anomalous group velocity dispersion spectral region.
References


1-W CW Tm-DOPED FLUORIDE FIBRE LASER AT 1.47 pm

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Indexing terms: Semiconductor lasers

A 1-W CW Tm-doped fluoride fibre laser operating at 1.47 pm and using an upconversion pump scheme is demonstrated. The pump source is an LD pumped Nd:YAG laser operating at 1.064 pm. The threshold and slope efficiency are 175 mW and 29%, respectively. Tunable operation from 1.445 to 1.51 pm is observed.

Introduction: We have successfully demonstrated an upconversion-pumped Tm-doped fibre laser operating at 1.47 pm, and observed a CW output of 100 mW and a Q-switched pulse with a peak power of 70 W [1]. We also achieved 25 dB amplification at 1.47 pm in a singlemode Tm-doped fluoride fibre [2]. This wavelength is a suitable pump wavelength for an EDFA (erbium-doped fibre amplifier), with a high slope efficiency of over 80% [3]. A high-power 1.47 pm Tm-doped fibre laser is promising as the pump source for a high output power EDFA. In addition, as the fibre loss around 1.47 pm is observed. The pump source is an LD pumped Nd:YAG laser operating at 1.064 pm. The threshold and slope efficiency are 175 mW and 29%, respectively. Tunable operation from 1.445 to 1.51 pm is observed.

Fig. 1 1.47 pm fibre laser output power as a function of launched pump power

Result and discussion: Fig. 1 shows the 1.47 pm laser output as a function of the 1.064 pm launched pump power. 75% of the launched pump power was absorbed and the remainder was also almost completely absorbed (93%) after being reflected by the high-reflection mirror. However, 7% of the launched pump power appeared to be transmitted. The use of a longer fibre seemed to be effective for obtaining a higher slope efficiency. The threshold was 175 mW and the slope efficiency was 29%. A maximum output power of 1 W was achieved for a launched pump power of 3.6 W. The oscillation wavelength was 1.4756 pm for a 100 mW output and 1.4936 pm for an 800 mW output. The oscillation wavelength lengthened at higher pump powers because of a reduction in the H2 ground-state absorption tail around 1.5-0 pm and an increase in excited state absorption (ESA) from F2 to G4 around 1.45 pm.

It is possible to increase the output power further by increasing the pump power because the output power is proportional to the launched pump power of around 3.6 W. However, the threshold of the launched pump power to less than 3.6 W to avoid any damage to the fibre from the high-intensity pump light. A large core fibre should be effective in decreasing the intensity of the pump light focused at the fibre end and in avoiding any damage caused by high-intensity pump light as scattering centres in the fibre core.