trailing edges of driving pulses are separated in time. In Fig. 3 we plot a measured pulse train when the MOLM was driven with nearly square pulses. Obviously, to suppress interpulse energy transmission, the phase amplitude is $\Delta\Phi_{peak} = \Phi_m = 2\pi$. As previously, the reflected beam represents the complimentary train of dark pulses.

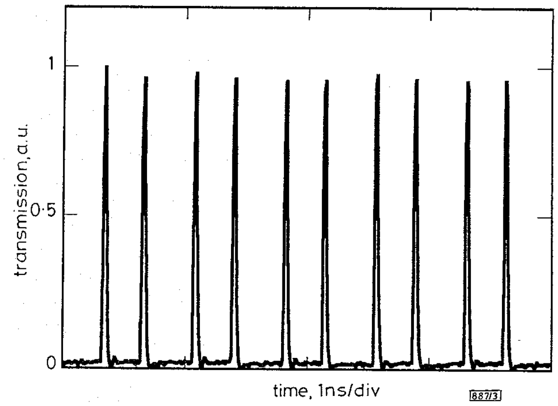

Fig. 3 *Oscilloscope trace of pulse train transmitted when loop is driven by nearly square-shape electrical pulses*

Two pulses per period correspond to leading and trailing edges of driving pulse, respectively

In conclusion, we have demonstrated optical pulse generation by switching the single frequency signal in the optical loop mirror incorporated phase modulator. The phase modulator provides a dual function: (i) optical spectrum broadening and (ii) instantaneous phase shifting between counter-propagating fields to achieve the switching. In the frequency domain this switching accomplishes spectral filtering required for pulse formation. Using this simple and robust technique, we have shown that low chirp pulses (either dark or bright) can be produced.

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Analysis of optical pulse train generation through filtering of an externally phase-modulated signal from a CW laser

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Indexing terms: Pulse generators, Grating filters, Gratings in fibres

The authors present an analysis of pulse-train generation through the filtering of the signal from an externally phase-modulated CW laser, and determine the exact filtering conditions for high quality pulse train generation.

Use of the external phase modulation and filtering of a CW laser signal for the generation of transform-limited optical pulses for soliton transmission was recently proposed and successfully implemented [1]. This idea is extremely attractive because of its simplicity. Furthermore, this method does not suffer from many of the shortcomings of other schemes such as large chirp, excessive timing jitter [2, 3] and modulator bias drift [4, 5].

The principles of pulse train generation through filtering of an externally phase-modulated CW laser signal were explained in [1]. However, exactly which part of the output spectrum should be removed for the most efficient generation of background-free pulse trains remained unclear. The theory in [1] was based on numerical simulations. In this Letter, we give analytical expressions for the pulse temporal and spectral widths against modulation depth, and predict the optimal filtering conditions.

The principle of pulse train generation is as follows: If a CW laser signal is sinusoidally frequency modulated, then the frequency chirp is zero at the extrema of the modulation. By spectral filtering of these components, a nearly chirp-free pulse train can be obtained [1]. To study this scheme analytically, we begin by writing the complex amplitude of the phase-modulated CW laser signal in the form

$$A(t) = A_0 \exp[iB\sin(\Omega t)] \qquad (1)$$

where B is the amplitude of modulation. The repetition rate of the phase-modulated pulse train is given by $R = 1/T = \Omega/2\pi$. Decomposing $A(t)$ into a Fourier series

$$A(t) = A_0 \sum_{n=-\infty}^{\infty} J_n(B)\exp(i\Omega_n t) \qquad (2)$$

where $\Omega_n = 2\pi n/T$ and $J_n(B)$ is the nth order Bessel function of the first kind, we write the output spectrum as a set of discrete components whose amplitudes equal $J_n(B)$. Fig. 1 shows spectra for different depths of modulation B. In the centre of the spectrum, the spectral components periodically change sign, whereas in the wings of the spectrum, the sign remains constant. From a physical standpoint, the effect of phase modulation is to increase the bandwidth of the signal without altering the intensity. Thus, the signal cannot be transform-limited, as is made apparent in the Fourier domain by the periodic sign changes in the middle of the spectrum. It is natural to suppose that an optimal transform-limited RZ (return-to-zero) train will be obtained by filtering out the periodically varying portion in the centre of the spectrum and leaving only one of the wings whose spectral components are in phase. We can thus obtain a transform-limited pulse train as shown in Fig. 1*b*. These pulses are soliton-like and, by appropriately matching the amplitude to the pulse duration, it is possible to obtain a highly useful soliton source.

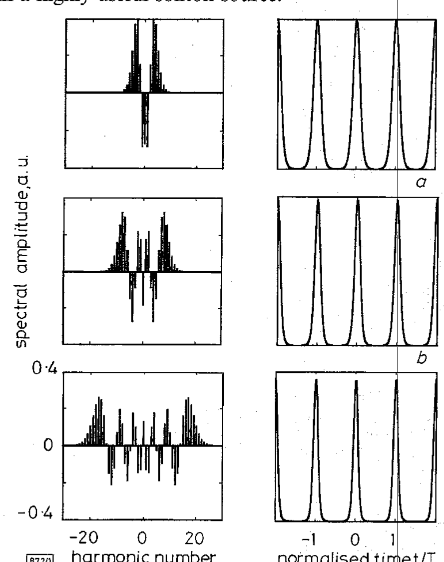

Fig. 1 *Spectrum of phase-modulated CW signal and pulse trains generated after spectral selection of anti-Stokes phase-mathced sideband*

a B = 1.5π
b B = 3π
c B = 6π

To calculate the precise spectral components that should be filtered out as a function of B, we recall that the first zero $B = j_n$ at which $J_n(B) = 0$ is given by [6] $j_n = n + 1.856n^{1/3} + 1.033n^{-1/3} + ...$ Thus, when

$$|n| > B - 1.856B^{1/3} - 0.115B^{-1/3} + \cdots \qquad (3)$$

all components will have the same sign. Using the formula [6]

$$J_n(n + zn^{1/3}) \simeq \left(\frac{2}{n}\right)^{1/3} \mathrm{Ai}(-2^{1/3}z) \qquad (4)$$

where Ai(x) is the standard Airy function, we infer that the full width at half maximum (FWHM) of the spectral components that are retained after filtering is given by $\Delta n \simeq 1.3B^{1/3}$, or $\Delta\nu = 1.3B^{1/3}/T$. The pulse train after filtering is transform limited, and the computer calculations yield $\Delta\nu\Delta\tau \simeq 0.38$, where $\Delta\tau$ is the pulse FWHM duration. (By comparison, we note that $\Delta\nu\Delta\tau = 0.357$ for a hyperbolic secant pulse and $\Delta\nu\Delta\tau = 0.441$ for a Gaussian pulse.) It follows that

$$\Delta\tau \simeq 0.34B^{-1/3}T \qquad (5)$$

Eqns. 3 and 5 are the main results of this Letter. Eqn. 3 gives the optimal filter position for producing a transform-limited pulse train and eqn. 5 predicts the output pulse characteristics. We note that the scaling $\Delta\tau \propto B^{-1/3}$ in eqn. 5 is consistent with the report in [1] that the energy in the output pulse trains changes from 90 to 45% as B increases from π to 7π.

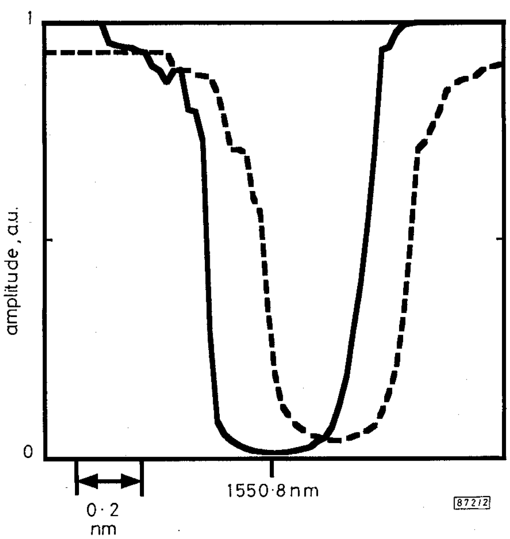

Fig. 2 *Practical example of fibre-grating filter transmission functions for two different filters*

——— f_1
– – – – f_2

This method of pulse train generation can be realised with a simple experimental setup. For example, instead of using high quality fibre-grating filters with a spectral width of ~2nm [1, 7], we may use more common fibre-grating filters whose spectral width is ~0.4nm. The 'width of the fibre-grating filter' means the width of the spectral region in which the spectral components of the signal are suppressed. We calculated the effect of such a filter on a modulated CW signal with the amplitude of modulation equal to π. The actual filter transmission functions from fibre-grating filters [Note 1] are shown in Fig. 2. A passage through one filter is not enough to erase the unnecessary spectral components, but by using two successive filters centred at different wavelengths, the selectivity of the spectral components can be significantly increased, as shown in Fig. 3. Gaussian filters can replace fibre-grating filters, and Gaussian filters will work better because they will not only select the desired spectral components, but will also help to symmetrise the spectrum.

Note 1: These fibre gratings were produced as a Fabry-Pérot pair by the United Technologies Research Center. The pair gratings were separated by cleaving the fibre between them. The gratings were then spliced to fibre pigtails, and characterised in G.M. Carter's laboratory.

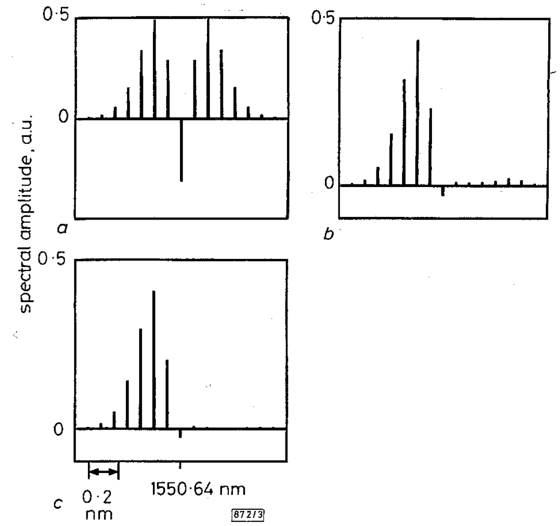

Fig. 3 *Spectrum of CW signal with amplitude of phase modulation $B = \pi$*

a Before filtering
b After two successive filterings by filter f_1
c After two successive filterings by filter f_2

In conclusion, we have calculated the spectrum of the phase-modulated CW laser signal, and have predicted the optimal filter position for transforming this signal into a train of soliton-like pulses. We have determined the temporal and spectral widths of these pulses, and have shown that we can obtain these pulse trains with low phase modulation amplitudes and with commercially available fibre-grating filters.

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