–17.7dB, and the crosstalk of the bar arm is –18.6dB with an operating voltage of 10V, which is the lowest value for a polymeric 2 × 2 optical switch, to the best of our knowledge. Owing to the relaxation of the poled polymers in the device, the operating voltage was increased to 12V after a few days. However, the operating voltage remains at 12V (operating for about six months) without change in the crosstalk.

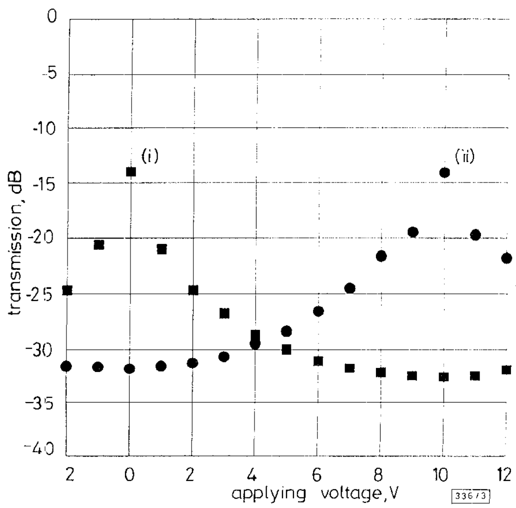

Fig. 3 *Measured transmittance of 2 × 2 switch using MBOA waveguide at λ = 1.3μm*

(i) cross-state
(ii) bar-state

Conclusion: We have demonstrated a new optical switch structure, the MBOA waveguide, which is a modified version of the BOA type waveguide to reduce the operating voltage and to improve the reproducibility of 2 × 2 photonic switches. The structure is insensitive to the processing environment and provides high performance 2 × 2 optical switches. The experimental results show 10V operating voltage and –18dB crosstalk, which are the best values for 2 × 2 polymeric electro-optic switches.

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Increasing the transmission distance of soliton communication systems by selective frequency shifts

A.L.J. Teixeira, G.P. Agrawal and J.R.F. da Rocha

Indexing terms: Optical communications, Solitons

The authors show that soliton interaction can be reduced considerably by selectively introducing a small frequency shift (~100MHz) on specific pulses of the bit stream. This technique can almost double the transmission distance of a soliton communication system. The block diagram of an electronic device for implementing the pattern-dependent frequency shifts is also presented.

Introduction: The soliton-based modulation format seems to be a potentially viable solution for improving the performance of dispersion-limited optical communication systems [1, 2]. Indeed, solitons have been transmitted over transoceanic distances at bit rates as high as 20Gbit/s in several laboratory experiments [3]. However, soliton interaction becomes a major limiting factor when solitons are packed tightly to increase the bit rate further [4]. To overcome this limitation, several schemes have been studied over the last few years, which improve the system performance by controlling the amplitude [5], the phase [6] or the polarisation of solitons [7].

In this Letter we present a novel frequency-coding scheme that allows the solitons to propagate over longer transmission distances under identical operating conditions. We also show how this scheme can be implemented in practice.

Effect of frequency shift on soliton interaction: Soliton interaction has been studied using perturbation theory [8]. The worst case of interaction occurs for solitons having the same phase and the same amplitude, which are attracted to each other, causing periodic collisions along the fibre. It is intuitively clear that in an in-phase pseudorandom bit stream, the soliton pairs with the least spacing will limit the whole system performance, since they have the shortest collision period (e.g. the '01100' sequence will have a shorter collision period a '01010' or '01110'). It is thus important to study how the collision distance of a single soliton pair can be increased by imposing a frequency shift.

We consider two solitons that have the same phase and amplitude, but their carrier frequencies have been shifted in opposite directions by a small amount Δf, so that the total optical field at the input of the fibre is written as:

$$u(t,0) = \mathrm{sech}\left(\frac{t}{T_0} - q_0\right)e^{-i2\pi(-\Delta f)t} + \mathrm{sech}\left(\frac{t}{T_0} + q_0\right)e^{-i2\pi(\Delta f)t} \quad (1)$$

where $2q_0T_0$ is the initial time separation, and T_0 is related to the pulse width as $T_{FWHM} = 1.763T_0$.

By generalising the results of [9], the normalised soliton position is found to change from its initial value q_0 as follows:

$$q(\xi) = q_0 + q_s + \ln\left|\cos\left(\frac{\pi}{\xi_p}e^{-q_s}\xi + \phi_s\right)\right| \quad (2)$$

where $q_s = -\ln\{1-s^2\}/2$ is the additional displacement of solitons induced by the frequency shift, $s = 2\Delta f T_0 \xi_p$ is the normalised frequency shift, $\xi_p = (\pi/2)\exp(q_0)$ is the normalised soliton-collision length [1], $\phi_s = -\sin^{-1}(s)$ is a phase shift, $\xi = z|\beta_2|/T_0^2$ is the normalised distance, and β_2 is the group velocity dispersion of the fibre.

Fig. 1 shows the soliton trajectories for several different values of frequency shift. A frequency shift causes an initial repulsion or attraction, depending on the sign of the frequency shift Δf. Therefore, if the correct sign of frequency shift is chosen, the frequency shift will cause an initial repulsion, and increase the collision length for the soliton pair. The frequency shift should be chosen such that the leading soliton is advanced and the trailing soliton is delayed compared with the case $\Delta f = 0$.

Maximum transmission distance: Eqn. 2 can be used to determine the maximum distance ξ_{max} that a soliton pair can propagate, before each soliton position shifts by an amount $\pm\Delta q$ from its initial position q_0. The result is

$$\xi_{max} = \frac{\xi_p}{\pi} e^{q_s}[\varepsilon \cos^{-1}(e^{-\varepsilon\Delta q - q_s}) - \phi_s] \qquad (3)$$

where $\varepsilon = \mathrm{sgn}(\Delta q - q_s)$.

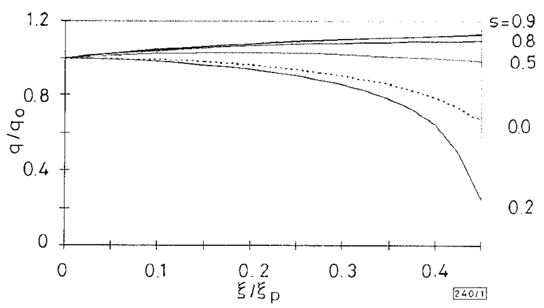

Fig. 1 *Soliton trajectories for in-phase soliton pair for several values of normalised frequency shift and $q_0 = 5.5$*

– – – – $s = 0$ case, zero frequency shifts

From the system-design viewpoint, it is useful to introduce the allowable soliton displacement Δt within the bit slot T_B, and define $\eta = \Delta t/T_B = \Delta q/q_0$ as the fraction of the bit slot that the soliton has shifted during its propagation. Fig. 2 shows the maximum transmission distance ξ_{max} as a function of η. The discontinuities in the plot show the sudden increase in the transmission distance occurring for $\Delta q = q_s$. The interpretation for these discontinuities is explained by the fact that for $\Delta q < q_s$ the maximum transmission distance ξ_{max} is set by soliton repulsion, whereas for $\Delta q > q_s$ it is the soliton attraction that determines ξ_{max}.

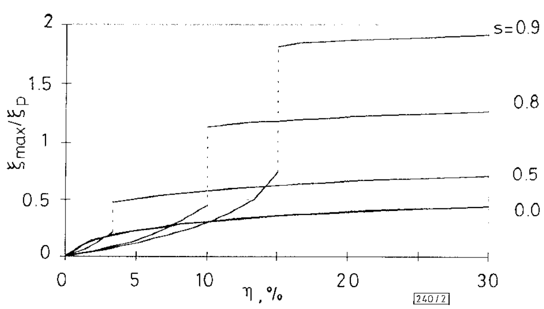

Fig. 2 *Maximum transmission distance against allowed displacement within bit slot for several normalised frequencies and $q_0 = 5.5$*

Discontinuity occurs at the point where ξ_{max} is limited by soliton attraction rather than soliton repulsion

As an example, we consider the case in which $\eta = 0.15$, which means that the soliton can move, at most 15%, from its initial position. Fig. 2 shows that for this case the transmission distance can be improved by a factor of 3.4 for a frequency shift such that $s = 0.8$ and $q_0 = 5.5$. Applying these results to a practical 20Gbit/s system (T_B = 50ps), the transmission distance without any frequency shift is ~2500km, whereas for the frequency shifted solitons ($s = 0.8$ or Δf = 170MHz) this becomes almost 8400km. These estimates are obtained for a 1.55μm soliton communication system by using $\beta_2 = -1$ ps²/km, and $q_0 = 5.5$.

Coding technique and practical implementation: In a practical system, all combinations of '1' and '0' are likely to occur. From the standpoint of soliton interaction, the combination of multiple '1' bits such as '00111100' is most problematic. However, in all such sequences, all '1' bits except those on the outside have their interaction forces balanced, at least to some extent. We propose to subject frequency shifts on the outer solitons only of each sequence of multiple '1' bits. In the sequence '011100' the second and fourth bits, counting from left to right, will be subjected to the frequency shifts.

Such a scheme can be implemented in practice by using the device shown in the block diagram of Fig. 3, which generates a three level electric signal which is '+1' or '–1' for solitons needing positive and negative frequency shifts, respectively, and is zero for all other bits. The device makes use of bit delays, decision circuits and adders only.

Numerical simulations were performed by solving the nonlinear Schrödinger equation, to characterise the benefits of this frequency coding scheme. The transmission distance improved only by a factor of ~2 due to the residual interaction among inner solitons of the multiple '1' bit sequences. Numerical results also show that the sequences containing an even number of '1' bits limit the transmission distance more than those containing an odd number of '1' bits. Moreover, the performance can be improved by optimising the frequency shift.

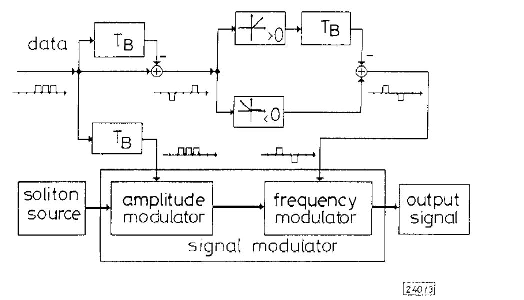

Fig. 3 *Block diagram of device that generates electronic signals suitable for imposing frequency shifts on outermost soliton of each sequence of multiple '1' bits*

Blocks with T_B represent a bit delay, blocks with a time-transfer function are positive (>0) and negative(<0) decision circuits, and remaining blocks are optical devices

Conclusions: In this Letter we have studied the effects of a small frequency shift on the interaction between two solitons. We found that the collision distance of an in-phase soliton pair can be increased substantially by small frequency shifts (~100MHz) of only the outermost solitons in a sequence of multiple '1' bits. The transmission distance be increased by a factor of ~2 by such a frequency-coding technique. We also have shown how this technique can be implemented in practice by using a simple electronic circuit.

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Optical millimetre-wave generation technique with high efficiency, purity and stability

L. Noel, D. Marcenac and D. Wake

Indexing term: Optical communications

A new technique is proposed and demonstrated for the optical generation of high power, high purity millimetre-wave signals, which uses optical heterodyning of two singlemode lasers to generate a beat signal in a photodiode. The lasers are in a series (master/slave) configuration, and very low phase noise is produced in the beat signal simply by subharmonic electrical injection of the slave laser.

Introduction: Future very high capacity radio networks are likely to use millimetre-wave radio because of the availability of large amounts of spectrum in this frequency range. Delivery of the millimetre-wave signals from a central site to many remote base-stations directly at the millimetre-wave frequency using analogue optical links is attractive from a cost and management perspective. For example, base-stations can be very simple since all the necessary signal processing and frequency upconversion can be done at the central site. A key component for such fibre-fed radio systems is an optical source of millimetre-wave signals. A new technique is proposed for the optical generation of millimetre-wave signals which is simple to implement and gives high power, high purity signals with wide locking range and tunability. Results from this technique have been obtained both from simulation and experimental measurement.

Description: The technique presented in this Letter is based on an optical injection locking experiment demonstrated by Schöll *et al.* [1]. Our work differs in that electrical injection is used to provide stability and purity to the output signal. Furthermore, our work also differs from earlier work by Goldberg [2], which used a master/slave laser arrangement in which the selection and locking of two modes from a slave Fabry Perot laser were used to generate a beat frequency in a photodiode. Although we also use a master/slave laser arrangement, in our case the lasers are singlemode devices and each contributes a single mode to the output. This technique gives the benefit of allowing great flexibility in the choice of beat frequency.

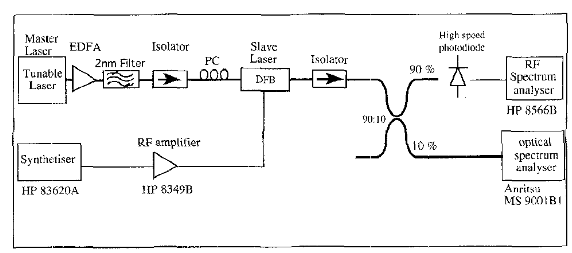

Fig. 1 *Experimental arrangement of subharmonic electrically injection-locked master/slave technique*

——— optical
- - - - electrical

The arrangement is shown in Fig. 1. Each laser contributes a single mode; the output of the slave laser (SL) consists of the slave mode and the mode from the master laser (ML). These modes beat together in a fast photodiode to produce the desired millimetre-wave signal. An electrical drive to the SL at a subharmonic of this beat frequency generates a series of sidebands. The ML mode injection-locks one of these SL sidebands which results in phase noise cancellation in the output signal. The purity of the resulting millimetre-wave signal is then derived from that of the electrical drive source, which can have subhertz linewidth for example.

Experimental setup: The ML signal was generated by a tunable laser from Radian Innova (Intun 1500), which allowed fine detuning of the optical frequency. After optical isolation, an erbium doped fibre amplifier (EDFA) was inserted to compensate for the optical insertion loss of the SL. The ML signal was filtered using a 2nm tunable bandpass filter to remove the amplified spontaneous emission from the EDFA, and was polarisation matched using a polarisation controller.

The SL is a 350μm long buried heterostructure distributed feedback laser which operated at a wavelength of 1554nm. This device had one anti-reflection coated facet, and was mounted in a fibre pigtailed high speed package (with fibre access to both facets) resulting in a 3dB bandwidth of 14GHz. The ML signal was coupled into the coated facet of this DFB and the output was taken from the uncoated facet. The master optical power level was adjusted using a variable attenuator to ensure that the output optical power from both modes were equal.

The two-moded optical signal from this arrangement was launched into a high speed edge-coupled *pin* photodiode via a 90:10 coupler, and the resulting beating signal was analysed using an RF spectrum analyser (HP 8566B) equipped with a preselected external mixer to cover the 40–60GHz range (HP 11974 U). The other arm of the coupler was used to monitor the dual-mode operation using an optical spectrum analyser (Anritsu MS9001A).

The SL was electrically modulated using an HP 83620A synthesiser in conjunction with a high power amplifier (HP 8349B) to provide an adequate range of power input levels.

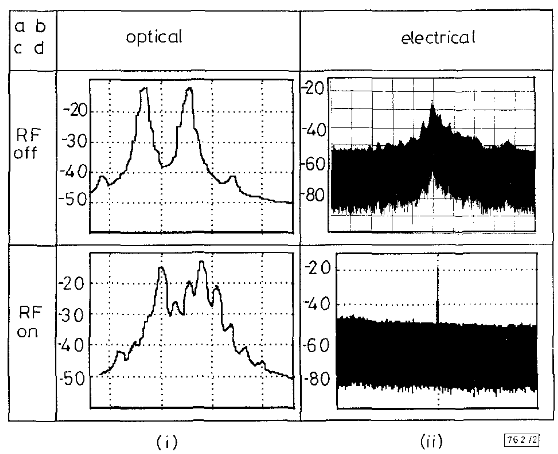

Fig. 2 *Optical and electrical spectra, measured with and without subharmonic electrical injection to slave laser*

(i) centre 1553.75nm
span 2nm
res. 0.1nm
(ii) centre 50GHz
span 20GHz
res. BW 3MHz
marker 49GHz, –24.9dBm

Results and discussion: Fig. 2 shows the optical and electrical spectra obtained by this technique. The spectra shown in the left column are optical, and those in the right hand column are electrical. The upper row shows the situation where no electrical modulation is present on the SL, and the lower row shows the situation when the electrical signal is switched on. The electrical drive to the SL was at 16.66GHz, although other (lower frequency) subharmonics were also used successfully but are not shown in this Figure. The drive power was 21dBm, which was required to compensate for the reduced response of the laser at this frequency. The ML optical signal was detuned from the SL mode by +50GHz with an optical power level in the fibre of 1.4mW.

With no electrical drive to the SL, Fig. 2*a* shows the CW ML and SL modes with a wavelength separation of 0.39nm, which corresponds to a beat frequency of 50GHz (shown in Fig. 2*b*).