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Self-sustained mode locking using induced nonlinear birefringence in optical fibre

P.E. Langridge, G.S. McDonald [1], W.J. Firth
Department of Physics and Applied Physics, University of Strathclyde, 107 Rottenrow, Glasgow G4 0NG, Scotland, UK

and

S. Wabnitz
Fondazione Ugo Bordoni, Via B. Castiglione 59, Rome, Italy

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A numerical study of self-sustained mode locking due to optically induced nonlinear birefringence is presented. The model incorporates a polarizer, a gain medium, a half-wave plate and a single-mode passive fibre in a ring cavity configuration. The mechanism exploits polarization instability in optical fibre with a weak, linear, intrinsic birefringence.

The Kerr effect in optical fibre has attracted considerable study since the theoretical prediction of soliton propagation in 1973 [1] and subsequent experimental verification in 1980 [2]. In a purely scalar treatment, the nonlinear Schrödinger equation approximately governs pulse propagation in a polarization preserving "single-mode" fibre when the input is polarized along one of the principal axes of the fibre. The input polarization state is then reproduced at the output.

If the input polarization is not aligned with one of the principal fibre axes, evolution is governed by a pair of coupled nonlinear equations [3–8] for the principal polarization modes. The output polarization state is now determined by the interplay between the intrinsic fibre birefringence and optically induced nonlinear birefringence arising from an intensity dependent contribution to refractive index.

Induced nonlinear birefringence effects were first observed in 1964 [9] when intense, elliptically polarized light emerged rotated on passing through various liquids. The phenomenon is used successfully in a number of fibre optic applications. These include intensity discriminators [10], logic gates [11] and the Kerr shutter or modulator [12] which can be used for optical sampling [13].

A more recent application is mode locking [14,15]. In particular, with rare-earth doped fibre lasers [14] both amplification and nonlinear birefringence are present within the same length of fibre. Here, we study a simplified model in which these effects are treated separately. We present a numerical study of self-sustained mode locking exploiting polarization instability [6] in optical fibre with a weak, linear, intrinsic birefringence. The mechanism relies on short, intense pulses launched close to the unstable fast mode transferring energy to the stable, orthogonally polarized, slow mode. In contrast, the work published to date depends predominantly on a nonlinear phase shift occurring between the principal polarization modes rather than on exchange of energy between them.

The unidirectional system studied is illustrated in fig. 1. A single pulse is injected into a length of optical fibre with a weak, linear, intrinsic birefringence. The input pulse excites both polarization modes and is of sufficient intensity to induce nonlinear bire-

[1] Present address: Université Libre de Bruxelles, Brussels, Belgium.

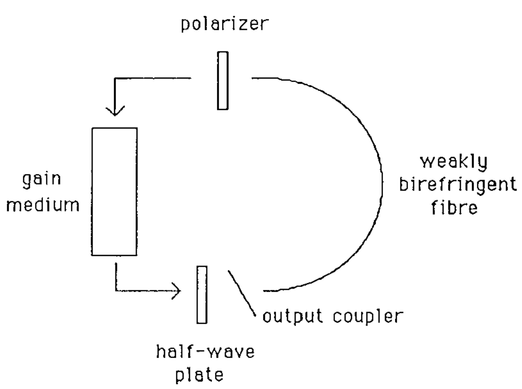

Fig. 1. Mode locked laser system exploiting polarization instability.

fringence. The light emerging from the fibre passes through a polarizer before being amplified. It is assumed that the gain medium does not alter the state of polarization. The amplified signal then passes through a half-wave plate which rotates the linear polarization transmitted by the polarizer. A fraction of the light emerging from the half-wave plate is coupled out of the system, the remainder re-entering the optical fibre to continue the cycle. The only losses are at the polarizer and output coupler.

Setting $u(z,t)$, $v(z,t)$ as the slowly varying complex amplitudes of the slow and fast fibre modes, respectively, nonlinear pulse propagation in the anomalous dispersion regime is governed by [6]:

$$\mathrm{i}\partial u/\partial z=\tfrac{1}{2}\partial^2 u/\partial t^2+(|u|^2+\tfrac{2}{3}|v|^2)u+\tfrac{1}{3}v^2u^*\exp(4\mathrm{i}kz)\,, \quad (1\mathrm{a})$$

$$\mathrm{i}\partial v/\partial z=\tfrac{1}{2}\partial^2 v/\partial t^2+(|v|^2+\tfrac{2}{3}|u|^2)v+\tfrac{1}{3}u^2v^*\exp(-4\mathrm{i}kz)\,, \quad (1\mathrm{b})$$

where the asterisk denotes complex conjugation. In view of the weak intrinsic birefringence, it is assumed that each mode has identical group velocity, as well as identical group velocity dispersion. The first term on the right-hand side of eqs. (1a) and (1b) governs pulse dispersion, reflecting the frequency dependence of refractive index. The remaining terms reflect the intensity dependence of refractive index. The second term governs the effect of self phase modulation while the third governs the effect of cross phase modulation. The last term on the right-hand side of each equation is responsible for the ellipse rotation phenomenon mentioned earlier. They are rapidly varying when the linear, intrinsic birefringence is large and may then be neglected in keeping with the slowly varying amplitude approximation adopted in the derivation of eqs. (1a) and (1b). However, differences in group velocity and group velocity dispersion of each mode must then be taken into account. The terms are included here since our interest concerns optical fibre with a weak, linear birefringence.

Equations (1a) and (1b) are in dimensionless form. t is a retarded "time", z measures "length" along the fibre and k is the half difference in the mode "propagation constants". Denoting the dimensional equivalent of the variables in eqs. (1a) and (1b) with a subscript R

$$t=(t_\mathrm{R}-\beta_1 z_\mathrm{R})/\tau\,, \quad z=|\beta_2|z_\mathrm{R}/\tau^2\,,$$

$$k=\tau^2 k_\mathrm{R}/|\beta_2|=\tau^2(\beta_u-\beta_v)/2|\beta_2|$$

and

$$u=\tau\left(\frac{\omega_0 n_2}{2c|\beta_2|}\right)^{1/2}u_\mathrm{R}\,, \quad v=\tau\left(\frac{\omega_0 n_2}{2c|\beta_2|}\right)^{1/2}v_\mathrm{R}\,,$$

where $\beta_1=\partial\beta/\partial\omega$, the reciprocal of the group velocity, $\beta_2=\partial^2\beta/\partial\omega^2$, the group velocity dispersion, both evaluated at the carrier frequency, ω_0, c is the speed of light in vacuum and n_2 is the Kerr coefficient. For anomalous dispersion, β_2 is negative. τ is an arbitrary time scale dependent on physical pulse width and pulse shape. β_u, β_v are the propagation constants of the slow and fast modes, respectively, due to the linear intrinsic birefringence.

With an appropriate transformation [6], eqs. (1a) and (1b) can be reduced to a form suitable for numerical integration by the split-step Fourier method [16].

The polarizer is assumed to possess two orthogonal axes, one of which is completely transmitting, light along the other leaving the system or being absorbed. With θ the angle between the transmission axis of the polarizer and slow mode of the fibre, the amplitude exiting the polarizer is

$$w_\mathrm{pol}(t)=u(L,t)\exp(\mathrm{i}\beta_u L)\cos(\theta)+v(L,t)\exp(\mathrm{i}\beta_v L)\sin(\theta)\,, \quad (2)$$

where $u(L, t)$, $v(L, t)$ are the amplitudes emerging from the length, L, of fibre. Equation (2) includes the effect of both the intrinsic and optically induced birefringences.

The linearly polarized light emerging from the polarizer is then amplified. The gain medium is modelled simply as a homogeneously broadened saturable amplifier [17]:

$$\tilde{w}_{\rm gain}(\omega)=\frac{\alpha}{[1+(\omega/\Delta\omega)^2](1+\epsilon I)}\,\tilde{w}_{\rm pol}(\omega)\,, \qquad (3)$$

where $\tilde{w}_{\rm pol}(\omega)$ is the Fourier transform of $w_{\rm pol}(t)$, α is the small signal gain, $\Delta\omega$ is the effective width of the gain, ϵ is the saturation parameter and $I=\int_{-\infty}^{\infty}|w_{\rm pol}(t)|^2\,{\rm d}t$. The temporal profile emerging from the gain medium, $w_{\rm gain}(t)$, is the inverse Fourier transform of $\tilde{w}_{\rm gain}(\omega)$.

The output from the gain medium is then incident on a half-wave plate. With ϕ the angle between the axes of the polarizer and those of the half-wave plate, the amplitude components re-entering the slow and fast modes of the fibre are

$$u(0,t)=Tw_{\rm gain}(t)\cos(\theta+2\phi)\,, \qquad (4a)$$

$$v(0,t)=Tw_{\rm gain}(t)\sin(\theta+2\phi)\,, \qquad (4b)$$

where T is the amplitude transmission factor of the output coupler.

For optical fibre, it is well known that combination of intrinsic and optically induced birefringences can lead to an instability of the fast mode. Numerical solution [6] of eqs. (1a) and (1b) has shown that the fast mode becomes unstable when the fibre beat length, $2\pi/(\beta_u-\beta_v)$, is longer than the soliton period, $\pi\tau^2/2|\beta_2|$. Depending on input, an intense pulse launched close to the fast mode may switch to the slow mode and stay there, or alternatively, continuously exchange energy with the slow mode. Only input aligned exactly with the fast mode will remain there. Transfer of energy between modes typically occurs over one or maybe several soliton periods.

We consider the case where the transmission axis of the polarizer is positioned close to the slow mode of the fibre. Then, with $\phi=0.25\pi$, propagation through the half-wave plate results in light re-entering the fibre close to the fast mode; the signals exiting the polarizer and half-wave plate being orthogonally polarized. Successful passage through the polarizer now relies on the fast mode being unstable, transferring energy to the slow mode.

We present numerical solutions of eqs. (1)–(4) for the initial condition

$$u(0,t)=A\,{\rm sech}(t)\cos(\theta+2\phi)\,, \qquad (5a)$$

$$v(0,t)=A\,{\rm sech}(t)\sin(\theta+2\phi)\,, \qquad (5b)$$

representing a single pulse injected into the length of the optical fibre. This particular choice of input, coinciding with the angle at which pulses enter the fibre on successive circuits, is not particularly significant but helps limit the number of passes necessary for final behaviour to become evident.

We consider operation at 1.55 μm. For an injected pulse width of 1 ps fwhm and typical group velocity dispersion, $\beta_2=-2.0\times10^{-26}\ {\rm s^2\,m^{-1}}$, the soliton period is approximately 25 m. For polarization instability, the soliton period must be shorter than the beat length. We take a refractive index difference between the slow and fast modes of 10^{-8} due to the intrinsic birefringence. The beat length is then 155 m at 1.55 μm.

Figure 2 typically illustrates formation of a self-sustained mode locked output when a 7 kW peak power pulse is launched into 40 m of fibre with an effective core area of 30 μm^2. Figure 2a, obtained with $\theta=0.05\pi$, $\phi=0.25\pi$, $\alpha=2.6$, $\Delta\omega=10$, $\epsilon=0.25$ and $T=\sqrt{0.8}$, shows output for the first 100 circuits. Figure 2b shows the output pulse at steady state; the crosses fit a sech^2 profile with the same peak value and width. The output pulse is close to transform limited with a time–bandwidth product, $\Delta t\Delta\nu$, of approximately 0.29. In real terms, the output has an approximate peak power and width of 5.2 kW and 520 fs fwhm, respectively. The final state illustrated in figure 2 remains invariant as the launched peak power is increased from 7 kW to 28 kW. However, a further increase may eventually alter the final output since polarization evolution on the first circuit becomes more complicated with increased peak power.

It is not entirely necessary for the signals exiting the polarizer and half-wave plate to be orthogonally polarized. With the transmission axis of the polarizer near, or even aligned with, the slow mode, ϕ should be such that light re-enters the fibre close to

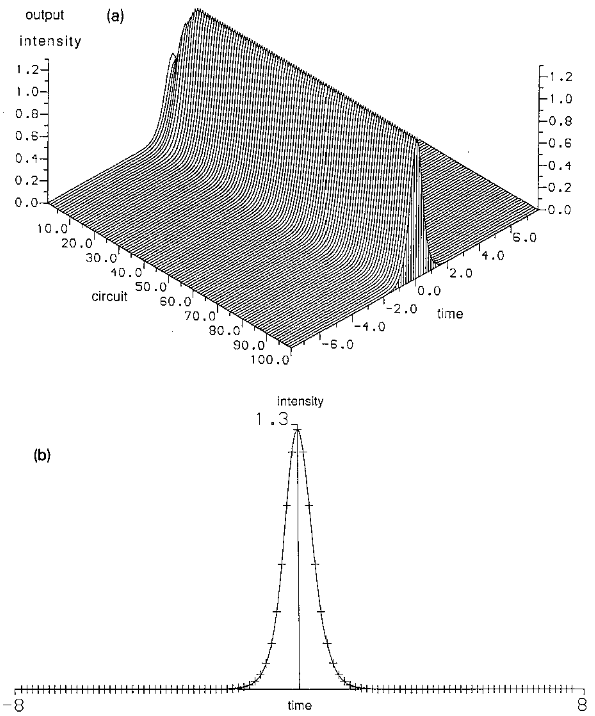

Fig. 2. Self-sustained mode locking obtained with $\theta=0.05\pi$, $\phi=0.25\pi$, $\alpha=2.6$, $\Delta\omega=10$, $\epsilon=0.25$ and $T=\sqrt{0.8}$. Behaviour is initiated by launching a 1ps fwhm, 7 kW peak power pulse into 40 m of fibre with an effective core area of 30 μm^2: (a) output for the first 100 circuits; (b) steady state output pulse. The crosses fit a $sech^2$ profile with the same peak value and width as the output.

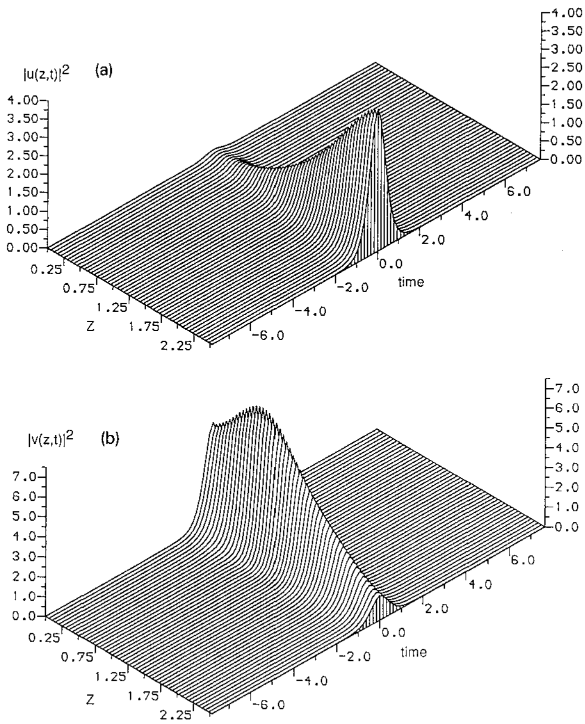

Fig. 3. Evolution of the two polarization modes for the steady state of fig. 2: (a) slow mode; (b) fast mode.

the fast mode to induce polarization instability.

Figures 3a and b show evolution of the slow and fast modes, respectively, for the steady state of fig. 2. Transfer of energy from the unstable fast mode to stable slow mode is clearly seen, with approximately 72% of the energy entering the fast mode switching to the slow mode.

Figure 2 relates to just above threshold. For $\alpha=2.59$ or less, amplification is insufficient to overcome losses at the polarizer and output coupler and decay results. Figure 4 illustrates behaviour as α is increased from 2.6, with remaining parameters as in fig. 2. The figure displays the dimensionless peak output intensity (crosses) and pulse width (circles) at steady state as a function of α. As α is increased, peak output intensity increases and pulse width decreases until a period doubling bifurcation occurs for α around 3.08; output then alternating between two values on successive circuits. A more complete bi-

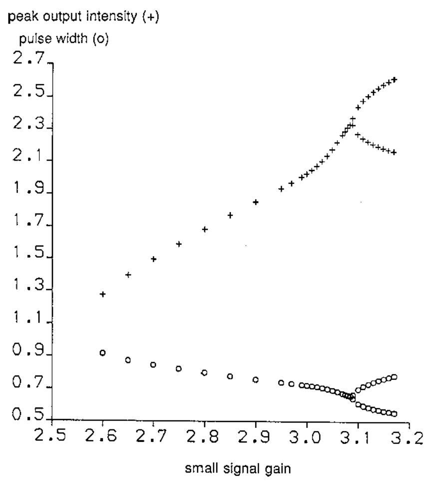

Fig. 4. Final behaviour as a function of small signal gain for the parameters of fig. 2. The crosses show peak output intensity, the circles pulse width.

furcation sequence is not presented since our primary interest is in the mode locking ability of the system shown in fig. 1 rather than its possible chaotic response. Also, pulse widths are approaching values for which eqs. (1a) and (1b) require revision [18].

The polarization properties of optical fibre are subject to a wide variety of perturbations [19]. Consequently, a low modal birefringence is difficult to maintain over any extended length, especially if the fibre is stressed as a result of bending or twisting. The mode locking mechanism presented here would thus be most practical for pulse widths of around 200 fs or less for which the soliton period is shorter than the fibre length over which low modal birefringence can be maintained, typically 1.5 m [20].

Erbium doped fibre provides a very attractive source of gain at 1.55 μm. Ideally, if a length of such fibre could be produced with a very low modal birefringence, amplification may be conveniently combined with polarization instability in a single fibre loop with polarization sensitive losses.

The mode locking mechanism presented here is one which exploits polarization instability in optical fibre with a weak, linear, intrinsic birefringence. Operation was initiated by injecting a single pulse into the length of optical fibre. The system may self-start with a proper choice of device parameters although, in general, the constraints imposed on θ and ϕ for optimum use of the instability are not too amenable to operation being built from noise. A configuration which would clearly not self-start is one with $\phi=0.25\pi$ and a length of fibre equal to an integer number of beat lengths. Polarization instability is not the only manner in which energy may be exchanged between the principal polarization modes of a birefringent fibre [21,22] and these alternative methods may better facilitate self-starting.

In summary, we have demonstrated, with a very simple model, the possible application of polarization instability as a mode locking mechanism. The steady state pulses are clean, pedestal free and close to transform limited. As the gain is increased, the pulses narrow but eventually show a period doubling instability.

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