

Soliton propagation and polarization mode-locking in birefringent optical fibres

V V Afanasjev and A B Grudinin

Russian Academy of Sciences, General Physics Institute, Vavilova Street 38, Moscow 117942, Russia

Received 31 July 1992, in final form 5 May 1993

Abstract. Soliton propagation in polarization-preserving fibres is analysed. Based on the coupled nonlinear Schrödinger equations we derive an analytical approximation for such type of soliton propagation. Exploitation of soliton polarization properties for passive mode-locking in fibre lasers is also considered.

1. Introduction

In recent years much work has been devoted to the development of erbium-doped fibre lasers [1–9], because a broad gain bandwidth centred nearly $1.54 \mu\text{m}$, negative group velocity dispersion and tight confinement of optical field allow the exploitation of nonlinear optical effects for very efficient generation of ultra-short optical pulses.

In the last few years several schemes of fibre soliton lasers have been reported [2–9]. Experimental study of such lasers has revealed a strong influence of fibre birefringence on laser output characteristics.

Polarization properties of optical fibres manifest themselves more clearly in mode-locked systems based on polarization switch [7–9]. It is interesting that the desirable effect can be reached in both linear [7] and ring configurations [8, 9].

Thus the problem of soliton propagation in birefringent optical fibres becomes of considerable interest and various aspects of the problem have been studied in many papers [10–15].

As has been shown [10–12] a bound state of orthogonally polarized solitons can exist in fibres with arbitrary birefringence provided there is compensation of polarization time delay by the group velocity dispersion that causes spectral separation of orthogonal components. Formally it means that, if input conditions for the coupled nonlinear Schrödinger equations have a properly designed spectrum, the term describing birefringence can be omitted.

Another soliton behaviour occurs if an initial pulse has unshifted spectral components. In this case there will be a transient region, characterized by an oscillating behaviour of the orthogonal spectral components and depending upon the value of birefringence this process might result in formation either of a single soliton with coupled polarization components or two independent solitons with an orthogonal state of polarization.

Thus the problem of soliton propagation in an optical fibre has in fact two aspects.

The first question is concerned with polarization evolution of the steady bound state of orthogonally polarized solitons. This problem is closely related to an effect of polarization intensity discrimination which plays a key role in the operational principle of a passive mode-locked laser based on polarization switch [8, 9], and in the general case this problem

$$i \left(\frac{\partial \psi_2}{\partial z} - \delta \frac{\partial \psi_2}{\partial \tau} \right) + \frac{1}{2} \frac{\partial^2 \psi_2}{\partial \tau^2} + (|\psi_2|^2 + \gamma |\psi_1|^2) \psi_2 = 0 \quad (1)$$

where $\gamma = 2$ for circularly polarized eigenmodes ψ_1 and ψ_2 and $\gamma = 2/3$ for linearly polarized ones. $\delta = B\tau_0/(2|k''|)$ and B is a fibre birefringence.

Since we consider here a steady bound state, then $\delta = 0$. These equations have the well-known exact soliton solution

$$\psi_i(\tau, z) = A_i \operatorname{sech}(\tau) \exp(-i\Gamma_i z) \quad i = 1, 2, \quad (2)$$

where A_i, Γ_i are some constants, and the relationship between A_i, Γ_i may be found by direct substitution of (2) to (1). However, solution (2) exists only in three particular cases: (i) Manakov's case, when $\gamma = 1$, (ii) only one polarization is excited $A_1 = 1, A_2 = 0$, or vice versa, (iii) the symmetric case $A_1 = A_2 = 1/\sqrt{1+\gamma}$.

We seek an approximate solution in the form (2), where now A_i and Γ_i are functions of the polarization angle α . Let us introduce the unknown real soliton amplitude $\rho(\alpha)$, then $A_1 = \rho(\alpha) \cos \alpha, A_2 = \rho(\alpha) \sin \alpha$. The function $\rho(\alpha)$ should satisfy the boundary conditions $\rho(0) = \rho(\pi/2) = 1, \rho^2(\pi/4) = 2/(1+\gamma)$ and should be periodical with period $\pi/2$. To find this function in an explicit form, we substitute (2) into (1)

$$\cosh^{-3}(\tau) [(\Gamma_i - 1/2 + S_i) \cosh^2 \tau + (1 - S_i) \sinh^2 \tau] A_i = D_i \quad (3)$$

where $S_i = A_i^2 + \gamma A_{3-i}^2$, and $D_i = D_i(\tau)$ are the discrepancies. These discrepancies arise in the right-hand side of (1) because we use the approximation (2) instead of exact solution, and we suppose that $|D_i|$ do not depend on z . We assume that Γ_i should satisfy the relationships

$$\Gamma_i = 1/2 - S_i \quad (4)$$

