Design of a Dual-Channel Modelocked Fiber Laser that Avoids Multi-Pulsing

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Abstract: Multi-pulsing competes with multi-channel modelocking in fiber lasers and can suppress it. We study the conditions to achieve stable dual-channel modelocking, and we propose a design that avoids multi-pulsing.
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1. Introduction

Multi-channel modelocked fiber lasers have many potential applications in different fields, such as wavelength-division-multiplexing (WDM) optical communication systems and optical spectroscopy [1, 2]. It has been observed experimentally that the phase of different WDM channels can be locked, which corresponds physically to a rapidly modulated pulse [2]. With an appropriate gain profile, a system in which a signal in a single channel is modelocked can transition into a signal in which two channels are simultaneously modelocked as the pump increases [1]. However, it is also possible for a multi-pulsing instability to occur [3] that prevents simultaneous modelocking in both WDM channels. In this paper, tudy the requirements to obtain dual-channel modelocking in a fiber laser while avoiding multi-pulsing. We present a design that achieves this goal.

2. Theoretical model and results

We previously modeled multi-channel modelocking using couple equations [1]. However, this model left out the effect of four-wave mixing. Here we use a full averaged model that contains both energy and phase interactions, focusing on a dual-channel system. This work is a starting point for understanding the requirement for stable operation of multi-channel systems with a large number of channels. To model this system, we use the Swift- Hohenberg equation [4], which is the simplest model that has a quartic linear gain profile in the frequency domain and thus includes the effect of a two channel filter. It can be written

$$\frac{\partial u}{\partial z} = -i\phi u - D_1\frac{\partial u}{\partial t} + \frac{g\left(|u|\right)}{2}u - \frac{l}{2}u - \frac{iD_2}{2}\frac{\partial^2 u}{\partial t^2} + i\Gamma|u|^2 u + \delta|u|^2 u - \sigma|u|^4 u + \alpha_2\frac{\partial^2 u}{\partial t^2} + \alpha_4\frac{\partial^4 u}{\partial t^4}\,, \qquad (1)$$

where z is normalized to a proposed cavity length L_c, t is normalized with respect to the dispersive time, and u is normalized with respect to the nonlinear amplitude, so that the coefficients of the chromatic dispersion term $-(i/2)\partial^2 u/\partial t^2$, and the Kerr nonlinearity term $i|u|^2 u$ are equal to 1. Other parameters per roundtrip are the phase rotation coefficient ϕ, the linear time delay D_1, the linear gain $g(|u|)$, the linear loss l, the saturable absorption coefficients δ and σ, and the gain filter coefficients, α_2, α_4. The filter profile in the frequency domain is $\exp\{\alpha\,[\omega^2 - (0.5\omega\ )^2\,]^2\}$, where ω is the angular frequency, $\omega = \Omega\ (\beta\ L\ )^{0.5}$ is the frequency separation between the two channels, where Ω_{sep} is the filter separation in unit of Hz, β_2 is the cavity dispersion, and $\alpha_2 = -2\alpha_4(0.5\omega_{sep})^2$. We use a slow saturable gain, $g(|u|) = g_0/(1+\int|u|^2 dt/E_s)$, where g_0 is the unsaturated gain and E_s is the saturation energy. An increase in the pump power corresponds to an increase in $E_{s.}$

The filter bandwidth is set at 0.3, which corresponds to nearly 100 GHz bandwidth when the cavity length L_c is 10 m and $\beta_2 = -20$ ps^2/nm. When $E_s = 0.5$, we find that modelocking occurs in only one frequency channel. In Fig. 1, we show the pulse profile in the time domain and the frequency domain. In this case, the filter separation is $\omega_{sep} = 0.6$, corresponding to $\alpha_2 = -23.76$, and $\alpha_4 = -32.92$. We observe different states of operation as the pump power increases. When the pump power increases from $E_s = 0.5$ to $E_s = 1.0$, energy appears in the second channel, leading to a rapid modulation in the time domain, as we show in Fig. 1(c) and 1(d). In this case, we have achieved dual-channel modelocking. By contrast, if the filter separation is $\omega_{sep} = 0.8$, so that $\alpha_2 = -23.04$, $\alpha_4 = -17.98$, then multi-pulsing occurs when E_s increases, and two well-separated pulses appear in the time domain [5, 6].

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A study of the linear stability of the stationary solutions provides additional insight into the competition between dual-channel modelocking and multi-pulsing [6]. It also provides an exact, quantitative prediction for the boundary between the two behaviors as the filter separation increases. In Fig. 2(c), we plot the dynamical spectrum for a stable single-channel modelocked solution in which the filter separation is $\omega_{sep} = 0.6$. The dynamical spectrum is a map in the complex plane of all the eigenvalues of Eq. (1), once Eq. (1) has been linearized about a stationary solution. The dynamical spectrum has a continuous spectrum and a discrete or point spectrum. When the stationary solution is stable, none of the eigenvalues has a positive real part. When the filter separation is $\omega_{sep} = 0.6$ and the pump energy increases, a complex conjugate pair discrete eigenvalues cross the imaginary axis and the single soliton evolves to a dual-channel modelocked state which we show the transient in Fig. 2(a). When the filter separation is $\omega_{sep} = 0.8$, the continuous spectrum intersects the imaginary axis. This corresponds to the growth of a new pulse, and multi-pulsing occurs which we show in Fig. 2(b). In our model, the boundary that divides the two states is when $\omega_{sep} = 0.77$. This suggests that in physical units, when the filter separation $\Omega_{sep} > 0.77(\beta_2 L_c)^{-0.5}$, which in our design corresponds to 274.03 GHz (nearly 2 nm in C band), multi-pulsing will impede achieving the dual-channel modelocking state.

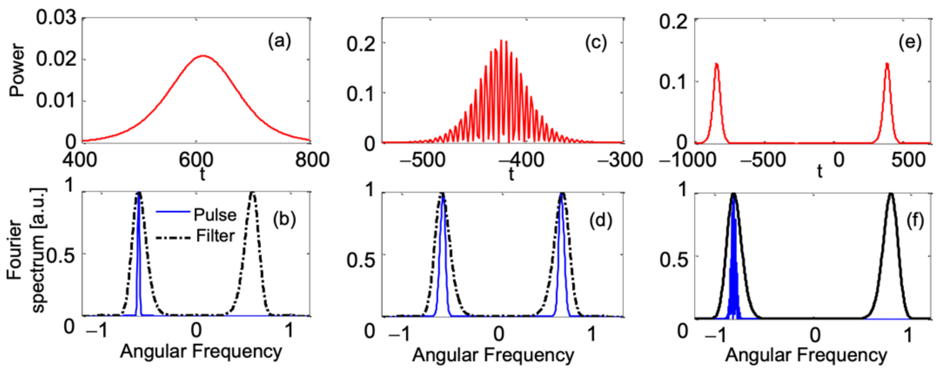

Fig. 1. Temporal and spectral profiles when (a)(b) $E_s = 0.5$, (c)(d) $E_s = 1$, and (e) (f) $E_s = 2.5$. We set $\alpha_2 = -23.76$, $\alpha_4 = -32.92$ in (a)(b)(c)(d) and $\alpha_2 = -23.04$, $\alpha_4 = -17.98$ in (e)(f). The Fourier spectra in (b)(d)(f) are normalized to its maximum.

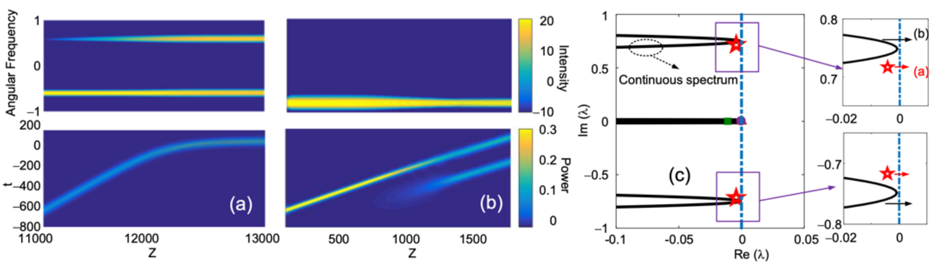

Fig. 2. Transients from single pulse modelocking to (a) dual-channel simultaneously modelocking and (b) multi-pulsing. (c) The dynamical spectrum of a stable single-channel modelocked solution. We set $\alpha_2 = -23.76$, $\alpha_4 = -32.92$ in (a)(c), and $\alpha_2 = -23.04$, $\alpha_4 = -17.98$ in (b). We set $E_s = 1$ in (a), $E_s = 2.5$ in (b) and $E_s = 0.5$ in (c).

3. Summary

In summary, we have investigated the conditions under which dual-channel modelocking can be achieved. We have found that when quartic gain filtering is used, a single modelocking pulse transitions to a dual-channel modelocked pulse when the pump power increases as long as the filter separation is below a threshold. Dual-channel modelocking competes with multi-pulsing modelocking. When the filter separation $\Omega_{sep} > 0.77(\beta_2 L_c)^{-0.5}$, multi- pulsing will impede dual-channel modelocking, so that it is not observed.

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