Multiple transmission filters for enhanced energy in mode-locked fiber lasers

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Abstract: We demonstrate that incorporating multiple sets of waveplates and polarizers in a ring cavity laser allows for the suppression of multi-pulsing and a significant enhancement (an order of magnitude) of the mode-locked pulse energy.

OCIS codes: (140.4050) Mode-locked lasers; (320.7090) Ultrafast lasers

1. Introduction

We present a viable technique for circumventing the ubiquitous multi-pulsing instability (MPI) limitations observed in mode-locked lasers [1]. Thus allowing for a potential increase in pulse energies by a final order of magnitude in order to compete directly with solid state lasers. Specifically, a simple yet effective technique is demonstrated for enhancing mode-locked energy delivery, namely multiple sets of waveplates and polarizers are applied to the cavity with pre-engineered transmission curve characteristics capable of circumventing MPI. The results suggest an order-or-magnitude increase is feasible. Moreover, a clear method is presented by which MPI and pulse energies can be easily increased. Figure 1 demonstrates the multiple transmission curve scenario using two sets of waveplates and polarizers. Each set is engineered so as to produce a desired transmission curve so that when used in combination, the MPI is suppressed and larger pulse energies are allowed. This concept can be generalized in order to include an arbitrary number of transmission functions that are based upon nonlinear polarization rotation, including nonlinear-optical loop mirrors, for instance.

2. Governing Equations and Theoretical Framework

The theoretical studies presented here are based upon integrating the key findings of recent papers [2-4]. Specifically, it is well known that the standard combination of waveplates and polarizer in a mode-locked cavity produces a periodic transmission curve. However, mode-locking models, such as the commonly accepted master equation, Taylor-expand the transmission curve so as to include only the first transmission window as a function of intensity. In [2], a geometrical description was developed showing that proper engineering of the transmission curve could allow mode-locking to naturally occur on the higher transmission windows instead of going through the MPI. However, this manuscript did not connect such an idealized transmission curve with a physically realistic cavity design. Concurrently, [3] showed that the master equation need not be truncated through a Taylor expansion. Rather, the entire physics of the nonlinear, periodic transmission could be retained in the mode-locked cavity equations so as to match the physically realizable system. These papers demonstrated that higher-energy mode-locked solutions could indeed be stable.

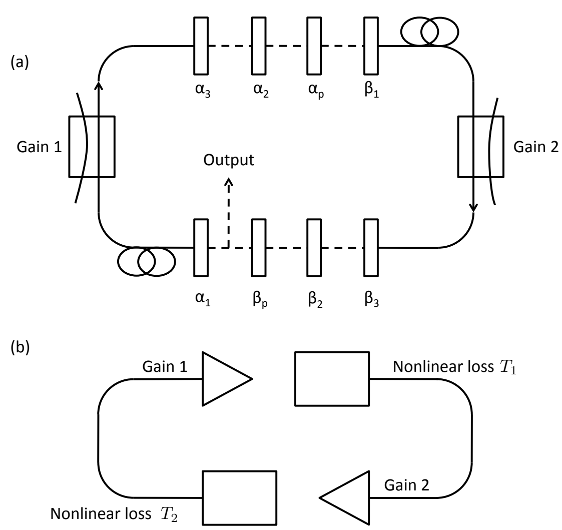

Figure 1: Fiber laser design with two transmission curves generated by multiple waveplate and polarizers. Engineering the nonlinear transmission curves allows for significant enhancement of pulse energy.

Building upon these findings, we perform full numerical simulations of the fiber laser cavity depicted in Fig. 1 when multiple transmission curves, or sets of polarizers and waveplates, are inserted into the cavity. The periodic transmission curve of each set of waveplates and polarizers are engineered so as to produce a prescribed transmission curve. The geometrical model presented in [1] is used to guide the engineering process of the transmission curves. It is suggested that additional sets of waveplates, fiber, and polarizer be inserted into the cavity so that multiple and distinct sinusoidal transfer functions can be combined to form a more sophisticated transfer function. In particular, the combination of two transfer functions, denoted by T_1 and T_2, are capable of producing an MPI suppressing behavior. Of critical importance is the effect of the two, versus one, transmission curves. In particular, the overall cavity transmission curve as a function of the electric field energy E will be approximated by the combination

$$T(E) = T_2(T_1(E)E)T_1(E) \quad (1)$$

where $T(E)$ is the effective transmission curve generated from the successive application of T_1 and T_2. It is this flexibility that allows for the creation of the ideal transmission curves suggested for overcoming MPI. Here, we build upon the previously established work with two nonlinear transmission functions [4] and demonstrate that multiple transmission functions can be cascaded together in order to provide an order-or-magnitude increase in mode-locked pulse energy. Figure 2 shows the results of using two transmission curves to more than double the mode-locked pulse energy and peak pulse intensity. Using multiple transmission curves allows for even greater increases in the laser performance.

3. Conclusions and Outlook

From a practical point of view and the theoretical and/or computational framework advocated here, simple design principles are established in order to design and engineer transmission functions capable of producing fiber laser cavities with superior performance in terms of energy enhancement. One of the primary difficulties in the theoretical modeling is the effort required to connect the desired transmission curves T_n (each of which has a few degrees of freedom describing its period, modulation depth, and offset) to the full cavity model and its large parameter space determined by the waveplates ($\alpha_1, \alpha_2, \alpha_3, \beta_1, \beta_2$ and β_3), the polarizers α_p and β_p, the fiber lengths (L_1 and L_2), the fast–slow axis alignments, and birefringence K_1 and K_2. This requires the engineering and nonlinear mapping of a high-dimensional parameter space to generate the desired transmission curve $T(E)$ that has a periodic structure and whose troughs remain above the small signal gain limit [2]. Although at first such a large parameter sweep seems rather daunting, it also suggests that there is a great deal of flexibility in engineering almost any periodic transmission curve desired, thus potentially allowing for upwards of an order of magnitude increase in energy if mode-locking can be achieved on the third, fourth or higher period of the periodic transmission window.

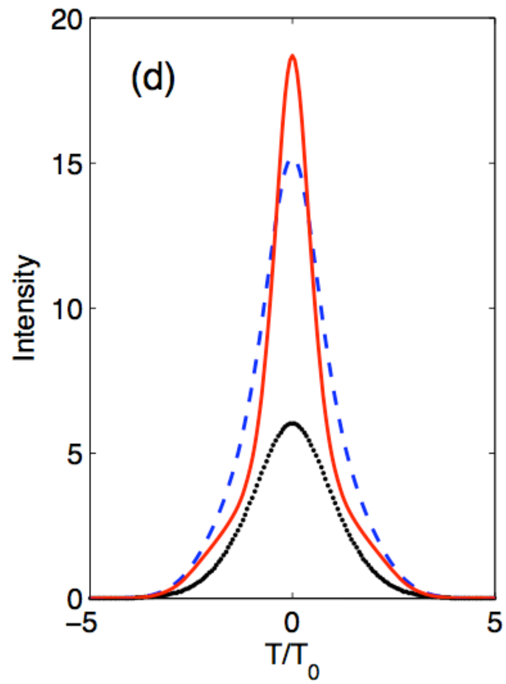

Figure 2: Maximum energy output mode-locked pulse profile for a single transmission function (black dotted line) along with the maximal energy pulses for the maximal energy (blue dotted line) and maximum peak intensity (red line) using two transmission curves. The two transmission curves suppress the multi-pulsing instability, allowing for significant enhancement in performance.

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