Amplitude of Pump-to-Signal Modulation in a Tm-doped Fiber for Active Mode-locking

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Recently, we proposed and demonstrated a mode-locked Tm-doped fiber (TDF) laser using a technique termed "active mode-locking via pump modulation" (AMPM). The cavity gain is modulated via pump modulation, of which the modulation frequency is matched with the free spectral range of the cavity. With the AMPM method, we achieved a mode-locked TDF laser with a transform-limited pulse width of 4.4 ps, a spectral bandwidth of 0.9 nm and a repetition rate of 12.9 MHz. However, the basic models for mode-locking assume a constant value of gain. In order to take pump modulation into account, the rate equations should be solved with the population-inversion density is modulated with sinusoidal pump power so that the lifetime of upper state can be included. Here, we investigate a pump-to-signal modulation transfer function in a TDF numerically and experimentally for understanding the mechanism of the AMPM method.

Error! Reference source not found. is the experimental setup for measuring the amplitude of the modulation index of the 2 μm output signal. The intensity of 1.57 μm pump is modulated by an optical intensity modulator and then amplified by a Er-doped fiber amplifier. The pump and the signal are coupled into the 4m-long TDF through the first 1550/2000 nm wavelength-division multiplexing (WDM) coupler. The second WDM coupler separates the pump and the signal. The intensity of the signal component at the modulation frequency is measured by an electrical spectrum analyzer connected with a high-speed photodetector. The 50/50 couplers are used for monitoring the intensity of input and output light simultaneously.

The modulation index of the output 2 μm signal can be calculated by

$$m_{2\mu m} = m_{1.57\mu m} \cdot H_{S\to S(\mathrm{EDFA})} \cdot H_{P\to S(\mathrm{TDF})}, (1)$$

where the $m_{2\mu m}$ and $m_{1.57\mu m}$ are the modulation index of the output 2 μm signal and the input 1.57 μm pump, respectively; $H_{S\to S(\mathrm{EDFA})}$ and $H_{P\to S(\mathrm{TDF})}$ are the amplitude of the signal-to-signal modulation transfer function of the EDFA and the amplitude of the pump-to-signal transfer function of the TDF, respectively.

The equation for the amplitude of the pump-to-signal transfer function is given by

$$H_{P\to S} = \frac{m_{P\to S}}{m_P} = \frac{(\alpha_S+\beta_S)[P_P^0(0)-P_P^0(L)]}{A_{eff}n_0 h\nu_P\sqrt{\omega_m^2+\omega_{eff}^2}}, (2)$$

$$\omega_{eff} = \frac{(\alpha_S+\beta_S)P_S^0(L)}{A_{eff}n_0 h\nu_S} + \frac{\alpha_P P_P^0(L)}{A_{eff}n_0 h\nu_P} + \frac{1}{\tau}, (3)$$

where m_P, $m_{P\to S}$ and ω_m are the modulation index of the pump, the modulation index of the output signal induced by the pump modulation and the modulation frequency, respectively; α_S, β_S, and α_P are the absorption coefficient of signal, the emission coefficient of signal and the absorption coefficient of pump, respectively; L, A_{eff}, n_0, and τ are the length, the effective mode area, the ion density and the fluorescence lifetime of the gain fiber, respectively; h, ν_S, ν_P, $P_P^0(0)$, $P_P^0(L)$, $P_S^0(L)$ are the Plank's constant, the frequency of signal and pump, the mean (unmodulated) input power of pump, the mean output power of pump and signal, respectively.

On the other hand, the equation for the amplitude of the signal-to-signal transfer function is given by

$$H_{S\to S} = \frac{m_{S\to S}}{m_S} = \frac{\sqrt{\omega_m^2+(\omega_{eff}+K)^2}}{\sqrt{\omega_m^2+\omega_{eff}^2}}, (4)$$

$$K = \frac{(\alpha_S+\beta_S)[P_S^0(0)-P_S^0(L)]}{A_{eff}n_0 h\nu_S}, (5)$$

where m_S is the modulation index of the input signal, $m_{S\to S}$ is the modulation index of the output signal induced by the signal modulation, the $P_S^0(0)$ is the mean input power of signal.

Fig. 2 shows the simulation results (blue-solid) and the experimental results (red-x) of the modulation index of the output signal with the different modulation frequency. We find good agreement between the simulation and experiment. The result shows that when we achieved mode-locking in the TDF fiber laser with the modulation frequency of 12.9 MHz, the modulation index of the signal for one round trip is estimated to be 2×10^{-4} %.

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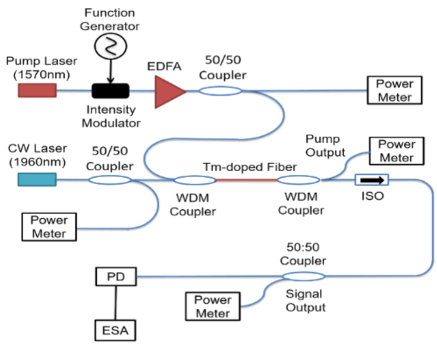

Fig. 1 Schematic of the experimental setup for measuring the amplitude of the modulation index of the output signal

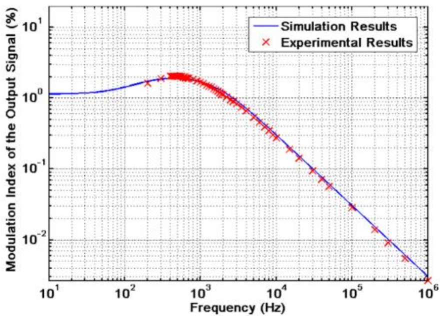

Fig. 2 The simulation (blue-solid) and experimental (red-x) results of the modulation index of the output signal