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Mode-locked all-fiber laser with high stability based on cobalt oxyfluoride

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Recent years have witnessed the exploration of fiber laser technology focused on numerous pivotal optoelectronic applications from laser processing and remote sensing to optical communication. Here, using cobalt oxyfluoride (CoOF) as the nonlinear material, a 156 fs mode-locked fiber laser with strong stability is obtained. The rapid thermal annealing technique is used to fabricate the CoOF, which is subsequently transferred to the tapered region of the microfiber to form the effective pulse modulation device. CoOF interacts with the pulsed laser through the evanescent field to realize the intracavity pulse shaping, and then the stable mode-locked pulse is obtained. The mode-locked operation is maintained with the pulse duration of 156 fs and repetition rate of 49 MHz. In addition, the signal-to-noise ratio is about 90 dB. Those experimental results confirm the attractive nonlinear optical properties of CoOF and lay a foundation for the ultrafast application of low-dimensional transition metal oxides.

Keywords: fiber laser; nonlinear materials; mode-locked fiber laser; saturable absorber.
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1. Introduction

Femtosecond fiber lasers have been investigated in such fields as coherent tomography, material precision processing/cutting, optical communication, scientific research, and industrial production fields because of their excellent advantages such as compact structure, fast heat dissipation, and strong stability[1,2]. After decades of rapid development, fiber lasers have made great progress, and some representative passive mode-locking methods, such as saturable absorber (SA), nonlinear polarization rotation (NPR) technology, and nonlinear optical loop mirror (NOLM), have been proposed[3–9]. Among them, the SA, which uses the nonlinearity of materials to convert continuous waves into an optical pulse, has become a research hotspot in recent years because of its special advantages in stability[10]. Since graphene films have shown excellent performance in near-infrared optoelectronic devices[11], the exploration of some potential nonlinear optical materials has set off an upsurge of research. So far, researchers have demonstrated the fascinating electronic and optical properties of a variety of novel two-dimensional (2D) nanomaterials, such as a topological insulator (TI)[12,13], black phosphorus (BP)[14–16], and transition metal dichalcogenides (TMDs)[17–21], which play an irreplaceable role in ultrafast photonics as SAs.

In recent years, transition metal oxides (TMOs) have become popular candidates for SAs due to their large nonlinear optical response. Scientists have enhanced the optical properties of TMOs by designing photonic band gap (PBG) structures and bandgap turning[22,23], making it comparable with other popular 2D nano materials in terms of generating ultrashort pulses. In 2017, Nady *et al.* synthesized a nickel oxide (NiO) SA and achieved femtosecond pulses at 1.5 μm[24]. Subsequently, titanium dioxide (TiO_2) has also been shown to be effective in the field of ultrafast photonics[25]. In 2019, Ahmad *et al.* successfully prepared zinc oxide (ZnO) nanorods and achieved stable mode-locked operation at 2 μm with pulse duration of 1.395 ps[26]. Although the above materials all have broadband gaps of more than 3 eV, the defects contained make them exhibit ideal optical absorption in the range of visible to near infrared[27,28].

As a member of TMOs, Co_3O_4 also has considerable nonlinear and linear absorption[22,29,30] and has been considered to be a promising nonlinear optical material in the near-infrared band[31]. It has proved that splendid *Q*-switching pulse sequences can be observed at the wavelength of 1–1.5 μm due to the nonlinear absorption characteristics of Co_3O_4 SAs[32,33]. The mode-locking operation associated with Co_3O_4 has also been

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subsequently reported. Ahmad *et al.* has demonstrated that Co_3O_4-based fiber lasers can generate the mode-locked pulses with a pulse width of 1.39 ps at 2 μm. The mode-locked system maintains good stability within 60 min[34]. Although Co_3O_4-based fiber lasers have been explored, the output pulse duration of fiber lasers using TMOs as mode-locked devices is only in the order of picoseconds. In order to improve the situation, some solutions have been explored. Recently, the research of transition metal oxyfluorides (TMOFs) has attracted the attention of researchers. The fluorine ion has an ionic radius similar to the oxygen ion, and some researchers have suggested that the introduction of F^- into TMOs can effectively reduce the ionic property of compounds and improve the optical properties of materials[35].

Here, cobalt oxyfluoride (CoOF), as one of the TMOFs, is studied experimentally in the fiber laser. The CoOF SA is prepared by rapid thermal annealing (RTA). The structure of the tapered fiber is selected to enhance the nonlinearity of the SA[36]. After coupling the CoOF SA as a mode-locked device into the ring cavity, a 156 fs ultrashort pulse is manifested at 1562 nm. In addition, a stable experiment is shown by the high signal-to-noise ratio (SNR) of 90 dB. The experimental results suggest the potential values of CoOF in stable ultrafast photonic applications.

2. Preparation and Characterization of CoOF SAs

CoOF was prepared by the RTA strategy[37]. In a high temperature environment, 2D CoOF was synthesized from cobalt fluoride tetrahydrate by thermal expansion, exfoliation, and oxidation. The prepared CoOF is subsequently transferred to the tapered region of the microfiber to form the CoOF-SA. The waist diameter of the microfiber is 15 μm. The chemical properties and characterization information of CoOF, including transmission electron microscopy (TEM), atomic force microscopy (AFM), and X-ray diffraction (XRD), were introduced in detail in Ref. [37].

The saturable absorption characteristics of SA were measured by the double balance detection method. The NPR-based space mode-locked laser provides a light source with a center wavelength of 1.5 μm. The pulse duration of the NPR laser is about 700 fs. Figure 1 shows the saturation absorption characteristics of CoOF, and the results are fitted by the following formula:

$$T = \frac{\alpha_s}{1 + I/I_{sat}} + \alpha_{ns}.$$

The modulation depth (MD) of the CoOF is as high as 56.79%, indicating that the combination of Co-F and Co-O bonds does help to improve the optical properties of the material. In addition, the non-saturated loss (α_{ns}) and saturation intensity (I_{sat}) of CoOF are 27.62% and 0.6581 MW/cm^2, respectively.

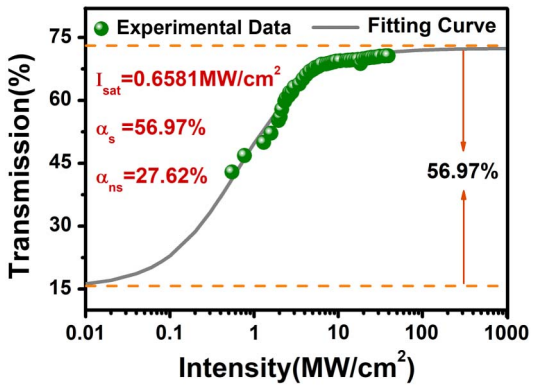

Fig. 1. Nonlinear optical transmission of CoOF-SA.

3. Experiment

Figure 2 shows a CoOF-based mode-locked fiber laser (MLFL), where the laser cavity includes a laser diode pump, an erbium-doped fiber (EDF) with a length of 0.4 m, an optical coupler (OC), a wavelength division multiplexer (WDM), a polarization controller (PC), an isolator (ISO), and a CoOF SA. The length of the whole ring cavity is 4.06 m. The signal light generated by the pump enters the laser cavity through the WDM and is amplified by the EDF. A small part of the output light from the 80:20 OC provides convenience for real-time signal measurement. The PC and ISO are assembled to adjust the polarization state and ensure the unidirectional transmission of the optical signal, respectively. The CoOF SA, as the main nonlinear modulation device in the cavity, is mainly used for pulse control and shaping. The optical characteristics of the laser are detected by a real-time oscilloscope, a spectrum analyzer, and an RF spectrum analyzer. In addition, the laser output through the OC terminal will be coupled to a power meter to obtain the output power.

4. Result and Discussion

Before CoOF is transferred to the surface of the microfiber, it is confirmed that mode-locking and *Q*-switching will not appear by changing the polarization state or increasing the power. After the CoOF SA with the MD of 56.79% is coupled into

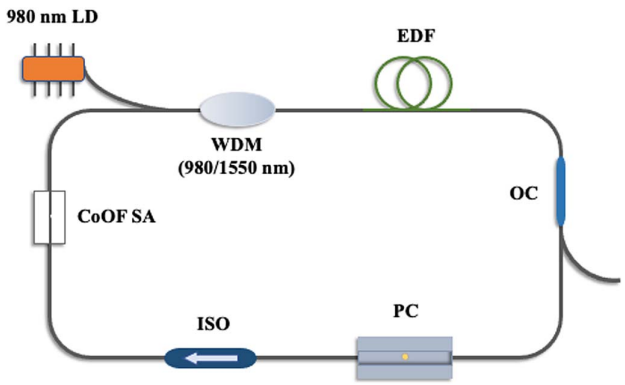

Fig. 2. Schematic diagram of high-stability MLFL cavity with CoOF SA.

the ring cavity, the mode-locked pulse is observed at 52 mW by rotating the PC. The mode-locked pulse remains stable after the pump power reaches 630 mW, the output power of obtained mode-locked laser is 20.1 mW, and, in this case, the relevant pulse energy is 0.409 nJ. The calculated optical damage threshold of the SAs is 0.643 mJ/cm^2. Figure 3 shows the output performance of the laser measured through the OC. The trace of the pulse train depicted on the oscilloscope is shown in Fig. 3(a), which indicates that the pulse interval of the pulse sequence is 20 ns. The measured autocorrelation (AC) trace of the pulse can be well fitted by a sech^2 profile, and the results indicate that the pulse duration of the laser is 156 fs. Figure 3(c) displays representative mode-locked spectra with a central wavelength of 1562.3 nm; meanwhile, the 3 dB bandwidth is 17.27 nm. In addition, the Kelly sideband is distributed on the spectrum, exhibiting that the system is operating in the soliton state. The calculated time bandwidth product (TBP) is 0.331, which shows that there is a small chirp, and the obtained soliton pulse almost approaches the transformation limit. The RF spectrum of the experimental system is studied, and the result is displayed in Fig. 3(d). When the resolution bandwidth (RBW) is 30 Hz, the measured repetition rate is 49.285 MHz, and the SNR is as high as 92 dB. No frequency drift and new frequency components are observed in the measurement process, which indicates that the fiber laser has good repeatability and long-term stability.

Table 1 demonstrates the performance comparison of MLFLs based on TMOs and some popular TMDs. It is noted that the MD of the CoOF SA is 56.79%, which is the largest among the materials listed in Table 1. Compared with TMOs (Co_3O_4, NiO, TiO_2, and ZnO), the CoOF-based mode-locked laser has obvious advantages in the generation of ultrafast pulses with high stability. The narrowing of the pulse has increased by almost an order of magnitude, and the increase in SNR is also above 34 dB, indicating that the introduction of F^- does improve the optical properties of materials. In addition, compared with classical TMDs (MoS_2, $MoSe_2$, and WS_2), the pulse duration of the CoOF-based mode-locked laser breaks through the important node of sub-200-fs, while ensuring the high stability of the system. This comparison strongly suggests that CoOF can be regarded as a potential candidate to be applied in the generation of ultrafast photonics with high stability.

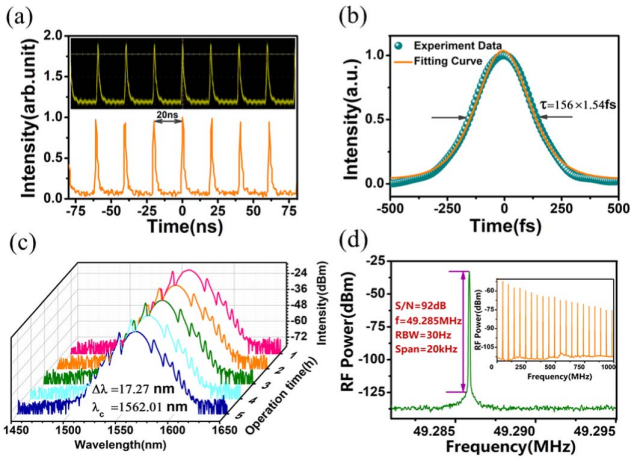

Fig. 3. (a) The pulse sequence. (b) The autocorrelation trace. (c) The spectra. (d) The RF spectrum.

Table 1. Comparison of MLFLs Based on TMOs and TMDs.

Materials	Modulation Depth (%)	Wavelength (nm)	Pulse Duration (ps)	SNR (dB)	Refs.
Co_3O_4	43.7	1958.1	1.39	46	[34]
NiO	39	1568.1	0.95	43	[24]
TiO_2	34	1979	10.29	58	[25]
ZnO	2.34	1945.45	1.395	50.5	[26]
MoS_2	19.48	1563.4	0.256	75	[38]
$MoSe_2$	0.8	1558	1	52	[39]
WS_2	11	1557	0.66	65	[40]
CoOF	56.79	1562.01	0.156	92	This work

5. Conclusion

In conclusion, by introducing fluoride functional groups into TMOs, the optical properties of CoOF SA have been improved. With the CoOF SA, the stable mode-locked system at 1562 nm has been delivered; at the same time, the mode-locked pulse sequence with output power of 20 mW, the pulse width of 156 fs, and the SNR greater than 90 dB is obtained, which shows an absolute advantage in similar lasers. The results have shown the effectiveness of CoOF in nonlinear modulation and provided a new feasible scheme for future research of strong stability mode-locked devices. Moreover, this research also shows the potential of CoOF as a broadband electronic material, which will provide a certain reference value for its multi-field application.

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