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Passively Q-switched erbium-doped fibre laser using cobalt oxide nanocubes as a saturable absorber

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ABSTRACT

We demonstrate a Q-switched Erbium-doped fibre laser (EDFL) utilizing cobalt oxide (Co\textsubscript{3}O\textsubscript{4}) nanocubes film based saturable absorber (SA) as a passive Q-switcher. Co\textsubscript{3}O\textsubscript{4} nanocubes are embedded into a polyethylene oxide film to produce a high nonlinear optical response, which is useful for SA application. It has saturation intensity and modulation depth of 3 MW/cm\textsuperscript{2} and 0.35\%, respectively. The proposed laser cavity successfully generates a stable pulse train where the pulse repetition rate is tunable from 29.8 to 70.92 kHz and the pulse-width reduces from 10.9 to 5.02 μs as the 980 nm pump power increases. This result indicates that the Co\textsubscript{3}O\textsubscript{4} is excellent for constructing an SA that can be used in producing a passively Q-switched fibre laser operating at a low pump intensity. To the best of our knowledge, this is the first demonstration of Co\textsubscript{3}O\textsubscript{4} film based fibre laser.

Introduction

Q-switching is a common method used for producing short and energetic pulse trains. The Q-switched Erbium-doped fibre lasers (EDFLs) has gained an increasing interest in the recent years due to their applications in many areas including material processing, sensing and medical treatment (1, 2). These fibre lasers are normally obtained from either active or passive techniques. Active techniques use a modulator, which is driven by an external electrical generator to produce Q-switching pulses (3, 4). On the other hand, passive Q-switching is normally realized by placing a saturable absorber (SA) inside the laser cavity. Therefore, in general, passive Q-switching methods are more useful and cost-effective than active methods which require additional switching electronics (5). Several types of SAs have been introduced in passive methods thus far and they include semiconductor SA mirrors (6, 7), transition metal-doped crystals (8–10), carbon nanotubes (11–14) and two-dimensional (2D) nanomaterials such as graphene and transition-metal dichalcogenides (TMDs) (15–17). These nanomaterials have been selected because of their excellent quantum confinement, strong ionic bonding and the absence of inter-layer interactions.

Although SESAM-based SAs have been widely used, they are expensive and their operation wavelength ranges are relatively small. The application of graphene is restrained by its low absorption co-efficient and zero band-gap characteristic. In order to use transition metal-doped crystals in Q-switched lasers we need free-space optical components, and this makes the systems more complex. TMDs materials such as molybdenum disulfide (Mo\textsubscript{S}\textsubscript{2}) and Tungsten disulfide (WS\textsubscript{2}) have also attracted much attention as they show good potential for pulse laser applications because of their unique absorption properties and thickness dependent band-gap (18–22). However, the process of fabricating TMDs based SAs is slightly complicated.

Transition metal oxides such as titanium dioxide (TiO\textsubscript{2}), zinc oxide (ZnO) and cobalt oxide (Co\textsubscript{3}O\textsubscript{4}) are another class of materials that exhibit nonlinear optical property. Over the past few decades, they have been intensively investigated not only due to optical nonlinearity but also its mechanical strength, thermal and chemical stability. For instance, several metal oxides films have a large nonlinear optical response with a third-order nonlinear susceptibility in the range between 10\textsuperscript{-8} and 10\textsuperscript{-7} esu. Among the transition metal oxides, Co\textsubscript{3}O\textsubscript{4} has the largest...
rate that increases from 29.8 to 70.92 kHz and the pulse width decreases from 10.9 to 5.02 μs as the pump power grows from 55 mW up to 165 mW.

Preparation and characterization of Co$_3$O$_4$ SA

First, Co$_3$O$_4$ nanocubes were synthesized by the simple technique reported in (27). Just as in a typical synthesis, 1 mmol Co(CH$_3$COO)$_2$·4H$_2$O was dissolved in 45 ml mixture of deionized water (DI) and ethanol (3:1) under bath sonication. Then 15 ml of urea solution (1 mmol) was added to the mixture and stirred for another 30 minutes. After that the mixture was placed in a 100 ml Teflon-lined stainless steel autoclave and kept in the preheated oven for 5h at 150 °C. The extracted precipitate of Co$_3$O$_4$ nanocubes was cleansed several times with DI water and ethanol by centrifugation. Finally it was dried in a hot air oven at 60 °C.

In order to fabricate Co$_3$O$_4$ SA, the nanocubes had to be embedded in a polyethylene oxide (PEO) thin film. The fabrication of thin film itself was done via solution casting route. Firstly, 1 gram of PEO was dissolved in 120 ml of DI water and put under constant stirring for 2 h at 50 °C. After that, sufficient amount of synthesized Co$_3$O$_4$ nanocubes was added into the above solution and kept under stirring for further 2h. Finally, the uniformly mixed slurry was casted on a Teflon coated Aluminum foil and dried at 60 °C.

Figure 1. Material characterization of Co$_3$O$_4$ nanocubes: (a) HRTEM, (b) FESEM, (c) XRD pattern and (d) Raman spectrum.

Figure 2. Nonlinear optical absorption characteristics of the Co$_3$O$_4$-based SA.

ratio of nonlinearity over linear absorption. It was found that Co$_3$O$_4$-based thin film possesses refractive index and extinction coefficient that change significantly with laser irradiation. In addition, the two absorption bands of Co$_3$O$_4$ centred at 410 and 725 nm make it a promising candidate for fabricating highly nonlinear transmission devices in the visible range. The optical properties of Co$_3$O$_4$ nanoparticles thin film are reported in (23–26).

Of late, the use of transition metal oxides such as ZnO and TiO$_2$ nanoparticles as SAs with good results have been reported in (23, 24). In this paper, we demonstrate a passively Q-switched EDFL by employing a Co$_3$O$_4$ film based SA for the first time. The laser successfully generates a Q-switched pulse train at 1561.6 nm with a repetition
was approximately 0.054 ± 0.002 mm as measured using Mitutoyo micrometer screw gauge.

The surface morphology of Co$_3$O$_4$ nanocubes was investigated using a field emission scanning electron microscope (FESEM). The high resolution transmission electron microscopy (TEM) was also employed to investigate the particle size and confirm the cubical shape of the nanocubes. The structural crystallinity and purity of the Co$_3$O$_4$ nanocubes were analysed by X-ray diffraction (XRD) and Raman spectroscopy, respectively. The XRD measurement was taken at a scan rate of 0.02 degree per second using Philips X’pert XRD equipment with copper K$_\alpha$ radiation ($\lambda$ = 1.5418 nm) while 514 nm green laser was used as a light source for the Raman spectrometer.

Figure 1(a) shows the XRD pattern of Co$_3$O$_4$ nanocubes. The diffraction pattern of pure Co$_3$O$_4$ displays prominent crystalline peaks at 2θ values of 18.1°, 30.9°, 36.4°, 44.2°, 54.9°, 58.6° and 64.4° which can be attributed to the (1 1 1), (2 2 0), (3 1 1), (4 0 0), (4 2 2), (5 1 1) and (4 4 0) planes, respectively (27). Figure 1(d) depicts the Raman spectra of Co$_3$O$_4$ nanocubes. The strong peaks at 192, 482, 517, 614 and 687 cm$^{-1}$ observed can be attributed to the $B_{1g}$, $E_g$, $F_{2g}$, $F_{2g}$ and $A_{1g}$ modes of Co$_3$O$_4$, respectively (28).

We determined the nonlinear optical response of SA Co$_3$O$_4$ using twin-detector technique. The mode-locked fibre laser was developed as an illumination source. It has a frequency repetition rate of 17 MHz, 900 fs pulse width operating at centre wavelength of 1550 nm. Changes in the output power of both detectors were recorded as the attenuation value was reduced gradually. A 3 dB coupler is used to split the output signal. One end of the coupler was connected directly to a power meter while the other was connected to the Co$_3$O$_4$-SA before another power meter. The transmissions, $T(I)$ at various input intensity were recorded and plotted as shown in Figure 2 after fitting using the following saturation model (29):

$$ T(I) = 1 - a_n \times \exp \left( \frac{-I}{I_{sat}} \right) - a_{ns} $$

where $a_n$ is the modulation depth, $a_{ns}$ is the non-saturable absorption, $I$ is the input intensity, and $I_{sat}$ is the saturation intensity. The modulation depth and saturation intensity of Co$_3$O$_4$ SA were determined to be 0.35% and 3 MW/cm$^2$, respectively.

**Laser configuration**

The schematic diagram of the fibre laser set-up is depicted in Figure 3, which consists of a 3 m long Erbium-doped fibre (EDF). The core and cladding diameters of the EDF were 4 and 125 μm, respectively, its numerical aperture is 0.16 and its Erbium ion absorption is 23 dB/m at pump wavelength of 980 nm. The EDF was pumped by a 980nm Laser Diode (LD) via a 980/1550-nm fused wavelength division multiplexing coupler. An isolator (ISO) was used to ensure unidirectional operation of the laser. The Co$_3$O$_4$ film is sandwiched between two ferrule connectors via a fibre adapter before it is inserted into the EDFL cavity to act as a passive Q-switcher. The film has an absorption of 3.0 dB at 1550 nm region. The output laser pulses are coupled out using a 80:20 coupler which keeps 80% of the oscillating light in the ring cavity. The total cavity length was ~8 m. A 350-MHz oscilloscope combined with a 1.2 GHz photo-detector, a radio frequency (RF) spectrum analyser, an optical power meter and an optical spectrum analyser with a spectral resolution of 0.07 nm were used simultaneously to monitor the output pulse train.
the pump power reached 55 mW, self-started Q-switched pulses were generated and it continued to be stable to the maximum pump power of 165 mW. The Co₃O₄ SA was maintained stably without thermal damage throughout the experiment. Figure 4 displays the output spectrum at 165 mW pump power. It shows that the Q-switched pulse operates at the central wavelength of 1561.6 nm with 3 dB bandwidth of 1.8 nm. Figure 5(a) illustrates the typical oscilloscope trace of the Q-switched laser obtained when the Co₃O₄ SA is added in the laser cavity when the pump power is fixed at 165 mW. The pulse train shows stable Q-switching operation with no fluctuations. The single pulse profile is shown in Figure 5(b), which indicates a full-width-half-maximum of 5.02 μs.

The population inversion improved with the increase in pump power from 55 to 165 mW, which provided more gain to saturate the SA. Consequently, the pulse width dropped from 10.9 to 5.02 μs while the pulse repetition rate increased from 29.8 to 70.92 kHz as shown in Figure 6. This phenomenon of increasing repetition rate and

**Results and discussion**

The performance of the proposed Q-switched EDFL with a ring configuration was analysed at various power of the 980 nm pump. Initially, a continuous wave (CW) laser was observed to start at pump power as small as 40 mW. As
decreasing pulse width as pump power increases is a distinct characteristic of passive Q-switching (30). The pulse width could be further shrunk by shortening the cavity length and increasing the pump power (31). The average output power and pulse energy against pump power are shown in Figure 7. It shows the maximum output pulse energy of 39.3 nJ at 115 mW pump power. To investigate the stability of our Q-switched pulse, the corresponding radio-frequency (RF) spectrum is shown in Figure 8. The RF spectrum shows the fundamental frequency of 70.92 kHz with a high signal-to-noise ratio (SNR) of ~60 dB. The SNR indicates a good pulse repetition stability (32), comparable to the output of other Q-switched fibre lasers based on TiO (33) and ZnO (34).

Conclusion

A passive Q-switched EDFL is experimentally demonstrated using Co3O4 film based SA as a Q-switcher. This is the first demonstration in which a Co3O4 has been used as the SA in a Q-switched fibre laser. The Q-switching operation was successfully achieved with repetition rate increases from 29.8 to 70.92 kHz, and pulse width decreases from 10.9 to 5.02 μs. These results verify that the presented Co3O4 has optical properties that make it advantageous for SA applications in cost-effective Q-switched EDFLs.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References


