Abstract

Generation of ultrashort laser pulses have gained a lot of interest due to their potential applications in optical telecommunication, nonlinear optics, medical treatment, and industrial material processing. Passively Q-switched and mode-locked fiber lasers are the most dominant techniques to generate those short pulses. Saturable absorbers (SAs) are the key components to start the process of short pulse generation. Looking for new SA with good optical properties and able to act as Q-switcher and mode-locker is always desired. In recent years, Transition metal oxides family has received much research attention due to its attractive optical, electronic, mechanical and physical properties.

In this work, two filmy SAs have been fabricated by embedding 0.5 wt% and 2 wt% copper oxide (CuO) nanoparticles into polyvinyl alcohol (PVA) separately. The optical parameters of the prepared SAs have been measured using balanced twin detectors technique. In 0.5 wt% CuO-SA (2 wt% CuO-SA), the practical values of modulation depth, saturation intensity and non saturable absorption were 3.5% (6.42%), 3.3 MW/cm^2 (9.23 MW/cm^2) and 3.7% (6%) respectively. A theoretical study for Q-switched erbium-doped fiber laser (EDFL) was carried out using modified rate equations and it is supported by simulation results obtained using MATLAB2018 software. The theoretical model takes into the consideration the practical parameters of the prepared SAs. Two prepared filmy SAs are incorporated into the laser cavity to realize Q-switching and mode-locking of EDFL. For 0.5 wt% CuO-SA and 2 wt% CuO-SA, stable Q-switched pulses were achieved at pump threshold of 70 mW and 158 mW with central wavelength 1560 nm and 1561 nm respectively. A maximum pulse energy of 66 nJ and 37 nJ, with a shortest pulse width of 2.6 μs and 3.6 μs were recorded at pump power of 159 mW and 300 mW.

By inserting 200 m long of standard single mode fiber (SMF) to compensate the cavity dispersion, a self-started soliton mode-locked operation is also obtained. In 0.5 wt% CuO-SA and 2wt% CuO-SA mode-locked, the emitting train of pulses have 1.7 ps and 1.8 ps pulse width and 983 kHz pulse repetition rate, while the pulse energy is 1.29 nJ and 2.16 nJ and output power is 1.27 mW and 2.13 mW with central wavelength 1560 nm and 1562.5 nm respectively. The experimental results indicate that 0.5 wt% CuO-SA can generate shorter pulse width at low pump threshold. Also these results present the CuO thin film is an appropriate SA for a pulse fiber laser operating with a low pumping power.

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LIST OF SYMBOLES

SYMBOLE	DESECRIPTIION	UNITS
Δv_p	Frequency gain bandwidth	Hz
$E_{laser}(t)$	Electric field of laser light	V/m
P_p^r	Pump rate of the active medium	W
f_{rep}	Mode spacing frequency	Hz
v_p	Axial laser modes frequency	Hz
τ_p	Pulse duration at FWHM	s
φ_p	Axial laser modes phase	
A_{gm}	Doping core area of the active medium	m^2
c	Speed of light in vacuum	m/s
d_{ol}	Dissipative optical loss of the cavity	
E	Electric field vector	
E_{out}	Theoretical output pulse energy	J
E_{ph}	Photon energy	J
h	Plank's constant	m^2kg/s
I_{sat}	Saturation intensity of saturable absorber	MW/cm^2
L	Length of optical fiber	m
L_c	Total ring cavity length	m
L_{gm}	Length of the gain medium	m
l_{sa}	Thickness of the saturable absorber	m
n	Refractive index	
N	Number of modes	
N_a	Saturable absorber photocarrier density	
n_g	Population inversion density	
N_{sat}	Saturation photocarrier density	m^{-3}
P_{out}	Theoretical output peak power	W
P_p	Pump power	W

SYMBOLE	**DESECRIPTIION**	**UNITS**
R_{oc}	Output coupler	
T_R	Round-trip transit time of the cavity	s
α_{nsat}	Non-saturable absorption of the saturable absorber	
α_s	Modulation depth of the saturable absorber	
γ_s	Inversion reduction factor	
Δt	Minimum possible pulse duration	s
$\Delta\lambda$	Modes spacing	m
λ	Central wavelength	m
σ_{gm}	Stimulated emission of the cross sectional area of the gain medium	m^2
τ_{gm}	Upper laser level life time of the gain medium	s
τ_s	Saturable absorber recovery time	s
τ_ϕ	Life time of the photon in the cavity	
ϕ	Photon density inside the laser cavity	m^{-3}
ϕ_{max}	Maximum photon density inside the laser cavity	m^{-3}
$\phi_{(t)}$	Photon density as a function of time	m^{-3}

LIST OF ABBERVIATIONS

ABBERVIATION	DESECRIPTIION
2D	Two Dimensional
AOM	Acousto-Optic Modulators
ASE	Amplified Spontaneous Emission
CNT	Carbon Nanotube
CSD	Chemical Solution Deposition
CuO	Copper Oxide
CW	Continuous Wave
EDF	Erbium-Doped Fiber
EDFA	Erbium Doped Fiber Amplifier
EDFL	Erbium-Doped Fiber Laser
EOM	Electro-Optic Modulators
Er^{3+}	Erbium Ion
FC	Fiber Connectors
Fe_3O_4	Ferric Oxide
FESEM	Field Emission Scanning Electron Microscopy
FL	Fiber Lasers
FTIR	Fourier Transform Infrared Spectroscopy
FWHM	Full Width at Half Maximum
GVD	Group Velocity Dispersion
KLM	Kerr Lens Mode-Locking
LD	Laser Diode
NA	Numerical Aperture
NALM	Nonlinear Amplifying Loop Mirror
Nd^{3+}	Neodymium Ion
NiO	Nickel Oxide
NLPR	Nonlinear Polarization Rotation
OSA	Optical Spectrum Analyzer

ABBERVIATION	DESECRIPTIION
OSC	Oscilloscope
OTDM	Optical Time Domain Multiplexing
PRR	Pulse Repetition Rate
PVA	Polyving1 Alcohol
QML	Q-switched Mode-Locked
RBW	Resolution Bandwidth
RF	Radio Frequency
SA	Saturable Absorber
SAM	Self-Amplitude Modulation
SEM	Scanning Electron Microscope
SESAM	Semiconductor Saturable Absorber Mirror
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SWCNT	Single-Walled Carbon Nanotube
TBP	Time Bandwidth Product
TI	Topological Insulators
TiO_2	Titanium Oxide
Tm^{3+}	Thulium Ion
TMD	Transition-Metal Dichalcogenides
VOA	Variable Optical Attenuator
WDM	Wavelength Division Multiplexing
Yb^{3+}	Ytterbium Ion
ZnO	Zinc Oxide

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