Q-switching of $\text{Yb}^{3+}$-doped fiber laser using a novel micro-optical waveguide on micro-actuating platform light modulator

Yunsong Jeong$^1$, Youngbok Kim$^1$, Andreas Liem$^2$, Klaus Moerl$^3$, Sven Hoefer$^2$, Andreas Tuennermann$^2$, and Kyunghwan Oh$^1$

$^1$Gwangju Institute of Science and Technology, 1 Oryong-dong, Buk-gu, Gwangju, South Korea
$^2$Institute of Applied Physics, Albert-Einstein-Str. 15, D-07745, Jena, Germany
$^3$Institute for Physical High Technology, Albert-Einstein-Str. 9, D-07745, Jena, Germany

koh@gist.ac.kr

http://allwise.gist.ac.kr

Abstract: We report a novel micro-optical waveguide (MOW) on micro-actuating platform (MAP) light modulator for Q-switched all-fiber laser applications. The light modulator employs a fused biconical taper (FBT) coupler, which acts as MOW, mounted on an electromechanical system, MAP, where an axial stress over the waist of FBT coupler is precisely controlled to result in modulation of output power. The modulator was implemented in a clad pumped $\text{Yb}^{3+}$-doped fiber laser cavity as a Q-switching element. Q-switching was successfully achieved at the repetition rate of 18.6kHz and average pulse energy of 1.4μJ. The proposed structure can be readily applied in power scaling up of all-fiber Q-switching laser systems.

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References and links

1. Introduction

As compact diode pump sources and single-mode fiber (SMF) compatible gain mediums have recently shown power scalabilities in CW operation, demands of all-fiber modulator for Q-switching are rapidly growing. Despite recent development in high power fiber laser technologies, efficient all-fiber Q-switching mechanism for the rare-earth doped fiber lasers is still in an early development stage. In contrast to mode locked ones, Q-switched fiber laser would find more versatile and practical applications such as in industrial processing, medical engineering, and sensing to name a few. Thus far, majority of attempts in Q-switched fiber lasers have been resorted to conventional bulk-optics such as acousto-optic modulators (AOMs) [1], electro-optic modulators (EOMs) [2] and saturable absorbers [3]. All-fiber Q-switching solution, therefore, will give an immediate and highly visible impact over further development of fiber laser technologies. Recently fiber compatible modulation schemes have been proposed utilizing fiber Bragg gratings (FBGs) and their spectral shift of transmission under mechanical perturbations [4-6]. Despite feasible outcomes, these FBG Q-switching schemes could suffer from weakening of FBG strength for high temperature and high power operation, which might be regarded as a fundamental bottleneck for power scaling-up.

The authors have proposed a novel opto-mechanical composite structure, micro optical waveguide (MOW) on micro-actuating platform (MAP) [7-9], where a fused biconical taper (FBT) coupler that serves as a MOW, was mounted on an electromechanical system, MAP. An axial stress over the waist of FBT coupler was precisely controlled to result in modulation of coupling constant. Broadband inter-band router [7], wavelength selective 1×4 switches [8] and high power variable optical attenuator [9] have been realized in all-fiber MOW on MAP structures.

In this paper we adopted this FBT coupler MOW on MAP structure for dynamic modulation of output power at a frequency close to the relaxation oscillation frequency of Yb^{3+} ions in silica to successfully demonstrate all-fiber Q-switching of Yb^{3+}-doped fiber laser, for the first time. The proposed device is composed of a special 2×2 FBT coupler whose resonance is located near 1 μm, close to the center of Yb^{3+} emission. Since the MOW on MAP light modulator is based on photoelastic effect induced change of coupling efficiency between two outputs of FBT coupler in a reciprocal manner, one output feeds the modulated optical signal back to the fiber laser cavity and another serves as output coupler. Design and fabrication of the proposed MOW on MAP structure, its dynamic response, and fiber laser Q-switching performance are discussed.

2. Operation Principle of MOW on MAP Light Modulator

FBT couplers used in this study were fabricated using conventional flame brushing technique [10], where twisted pair of two identical SMFs were fused and tapered by a traversing mini C_{3}H_{6}/O_{2} torch. As two cores become close to each other within a common cladding, the coupling starts by the interaction among guided modes, i.e., even and odd modes in the associated cores. Snyder et al. made an approximation of overlap field in order to calculate the coupling coefficient and the transfer power [11]. In the assumption of weakly guiding and infinite cladding fibers, the coupling coefficient is obtained as
\[ C(z) = \frac{\sqrt{2\Delta} U^2 K_d(Wd/\rho_0)}{\rho_0 V^3 K_0^i(W)} \]  

where \( \rho_0 \) is the fiber radius and \( d \) is the distance between two-fiber centers. \( U \) and \( W \) are the transverse wave numbers of the fiber. The \( K \)’s are modified Bessel functions of the second kind. The normalized frequency, \( V \), and the relative refractive-index difference, \( \Delta \), are following as

\[ V = \frac{2\pi}{\lambda} \rho_0 \sqrt{2\Delta}, \quad 2\Delta = \frac{n_{te}^2 - n_{te}^i}{n_{te}^i}. \]  

In the MOW on MAP structure, the refractive index in the coupling zone is changed when the glass is subjected to mechanical stress by photoelastic effect [12-14];

\[ \Delta n_r = C_b \sigma_z = C_b \frac{F_z}{A} \]  

where \( \Delta n_r \) and \( C_b \) are the refractive index change in radial direction and the photoelastic coefficients, respectively. \( \sigma_z \) and \( F_z \) are the stress component and tensile force in the axial direction. \( A \) is the cross-section area of the fiber.

Here we assumed that the axial stress component is the dominant, \( \sigma_z \approx \sigma_r \) and \( \sigma_\theta \), and for the guided mode along optical fiber, the refractive-index change in radial direction then influence the coupling constant. Besides the photoelastic effect, the actual dimension of the waveguide is changed by stress-strain relation [8]. These two effects, refractive index change by photoelastic effect and dimension change by stress strain relation, can flexibly modify the coupling constant to modulate the output of a 2×2 FBT fiber coupler, which serves as the basic principle for MOW on MAP device used in this study.

The schematic diagram of the device operation principle is presented in Fig. 1. A 2×2 FBT coupler has initially 100% transmission through one of two output ports at a certain wavelength with an appropriate coupling constant as shown in the upper diagram of Fig. 1. Under the influence of the axial stress over the coupling zone, the coupling constant is modified and subsequently the outputs vary reciprocally. Under repeated cycles of precisely controlled axial stress over the coupling zone, therefore, the device can effectively modulate the two output ports in a reciprocal manner. In order to obtain higher frequency response and lower polarization dependence, it is imperative to have a circular cross-section at the waist of coupling zone. The actual photograph of the cross-sectional morphology of the waist is shown in the inset photograph of Fig. 1.
Prior MOW on MAP applications [7-9] have been in a static operation with a response time greater than msec, which is not adequate for Q-switching of Yb fiber laser. In order to enhance the high frequency response, we further developed MOW on MAP structure by optimizing parameters such as the tapering length, cross-sectional morphology at the waist of the coupling zone, thickness at the waist, and actuator-coupler holder assembly structure. Note that the dimension of the waist is usually less than \( \approx 40\) micron, which forms MOW. This MOW is, then, mounted over a MAP, which provides axial displacements of less than 15\( \mu \)m to induce the compressive stress by PZT driven actuator and coupler holder assembly. The actuator-fiber holder assembly was designed to be on a precise linear translation rail so that only the axial stress could be applied over the coupling zone of MOW.

Actual photograph of the assembled MOW on MAP device is shown in Fig. 2. A 2\( \times \)2 FBT coupler with an optimal spectral and photoelastic response is mounted on holders. One of holders is fixed and the other is connected to PZT driven linear actuator. The actuator and the fiber holder are assembled on a precise linear translator. With an optimal combination of MOW on MAP structural parameters, the high frequency response was significantly improved compared to prior structures [7-9].

![Fig. 2. Actual photograph of assembled single stage MOW on MAP device.](image)

![Fig. 3. Spectral response with applied voltages of MOW on MAP modulator.](image)

To apply the device in the Yb\(^{3+}\)-emission range, the spectral response of the MOW was tailored using a specialty fiber having the cutoff wavelength at 920nm to secure single mode operation of the device in the wavelength range of 1060~1080nm. The SMF has a core diameter of 5.8\( \mu \)m and numerical aperture (N.A.) of 0.14. 2\( \times \)2 couplers were fabricated from this specialty fiber by appropriate fusion and tapering process. Fig. 3 shows the spectral response of the coupler before and after the mechanical perturbation in the MOW on MAP structure. At 0V, the transmission peaks around 1050nm along with the insertion loss of 0.74dB. By applying 23.5V corresponding to axial displacement of 15\( \mu \)m, the spectral response showed a \( \pi \)-phase shift decreasing the transmission at 1050nm by 23dB.
3. High frequency response of MOW-MAP light intensity modulator

After confirming the spectral response of the MOW on MAP, the output response of the device under high frequency modulation was further investigated. Fig. 4 shows the experimental setup for measuring frequency response of the device. The MAP was driven by the pulse generator followed by an electric amplifier circuit. A continuous wave (CW) Yb$^{3+}$-doped fiber laser operating at 1080nm was coupled to one of input ports and the output power was monitored using a photodector connected to an oscilloscope.

![Measurement setup for frequency response investigation.](image)

The modulated laser outputs were measured at various frequencies and the results are shown in Fig. 5.

![Frequency response of the MOW on MAP modulator.](image)

It was observed that the modulation depth decreases with the increasing frequency of driving voltage. Nevertheless, the switching speed increases up to 14μs for 18.6kHz, as shown in Fig. 5 (d). The rapid switching is immensely important for formation of Q-switched laser pulses. In order to further investigate the high frequency response, we measured the impulse response of
the modulator using a large bandwidth sampling scope and the measured spectrum is shown in Fig. 6.

As consistent with Fig. 5, the device showed a high response below 1kHz range. Besides this excellent low frequency characteristic, the device provided discrete peaks, around 3, 15, and 26kHz, which is attributed to unique electro-mechanical resonant frequency of the assembled MOW on MAP structure. We therefore have confirmed that newly proposed device could be also viable for intensity modulation of light at the frequency range over 15kHz. Note that this range is highly compatible to Q-switching of Yb³⁺ doped silica fiber gain medium.

Silica optical fiber has shown superb strength against axial stress [15]. In order to confirm stable operation of the device as a light intensity modulator, mechanical reliability and performance repeatability were tested by an automated cycle test with an excessive displacement of 200μm. After 500,000 cycles of axial stress, the device did not show any significant degradation, which provided a strong potential for reliable device performance. Further reduction of axial displacement requirement for π-phase shift is being attempted by the authors, which will improve reliability of the device as well as high frequency response.

4. Q-switching of Yb³⁺-doped clad pumped fiber laser using MOW on MAP device

An analytic relation between the formation of output pulses and the modulator switching speed has been established in prior Q-switching theory, for example as in the reference [16]. For a rapid switching after the initial population inversion is achieved, the pulse build-up time, $T_b$, and pulse width, $\tau_{\text{pulse}}$, are approximated as;

$$T_b = \frac{\tau_c}{r - 1}(25 \pm 5).$$

$$\tau_{\text{pulse}} = \frac{r \eta}{r - 1 - \ln r} \times \tau_c$$

where $\tau_c$ is the cavity lifetime, $r$ is the ratio of initial population inversion to threshold inversion after switching. $\eta$ is energy extraction efficiency for the conversion of initial stored energy into Q-switched pulse energy. If the modulator switches slowly with $\tau_{\text{pulse}}$ longer than $T_b$, multiple pulses could be generated and the initial inversion ratio significantly decreases resulting in reduction of the energy extraction efficiency. The relation between the initial inversion ratio $r$ and the energy extraction efficiency $\eta$ is calculated and the results are shown in Fig. 6.
Therefore we need a sufficiently fast switching speed to achieve an efficient Q-switching and we implemented the MOW on MAP modulation speed over 18.6kHz, as indicated in Fig. 5-(d), where the switching speed reaches 14μs that is significantly faster than the upper laser level life time of Yb\textsuperscript{3+} ion in silica host. The present modulation depth at this frequency, however, was rather shallow with approximately 5-6%.

![Fig. 7. Energy extraction efficiency versus initial inversion ratio.](image)

With the proposed MOW on MAP modulator, Q-switched Yb\textsuperscript{3+}-doped fiber laser cavity was constructed as shown in Fig. 8. The Yb\textsuperscript{3+}-doped double-clad fiber (DCF) had a D-shaped silica cross section along with circular Yb core to improve the pump-Yb interaction. The modulator has two output ports whose responses are reciprocal to each other. One of ports fed the signal back to the cavity and another was used as the laser output.

![Fig. 8. Q-switched Yb\textsuperscript{3+}-doped fiber laser setup.](image)

The system showed the peak power of 0.54μJ at 4.1W pump power and 1.4μJ at 5.2W. The repetition rate was 18.6kHz. Fig. 9 shows the laser output waveforms. It is noted that pulse duration did depend on pump power and pulse duration was 2.8, 2.0μsec for 4.1 and 5.2W of pump power, respectively. Pulse repletion rate was determined only by the driving frequency of MOW on MAP modulator. Further optimization of connectorization between the gain fiber and the device could improve the peak power and pulse duration.
Fig. 7. Q-switched laser pulses with pump powers of (a) 4.1W and (b) 5.2W.

With a proper fiber connectorization scheme between the double clad structure in the gain medium and conventional SMF in the modulator, the laser output power can be significantly enhanced and the investigation is being pursued by the authors. It is also noteworthy that the proposed modulator can sustain high power for both signal and pump due to its all silica fiber structure and scaling up of output power could be easily obtained.

4. Conclusion

All-fiber type of MOW on MAP light modulator has been presented for active Q-switching of Yb$^{3+}$-doped DCF laser. Adiabatic biconical structure converges the mechanical stress to the waist of the FBT coupler and efficiently modulated the output at high frequency ranges over 15kHz. The modulator has been implemented in a fiber laser cavity to serve as a Q-switch and at the repetition rate of 18.6kHz laser pulses of 0.54μJ and 1.4μJ were successfully obtained by pump powers of 4.1W and 5.2W, respectively, along with the pulse widths of 2.8 and 2.0 μsec. Further improvement in modulation depth and speed in the MOW on MAP structure could further increase the efficiency and power up-scaling capability along with proper fiber connectorization.

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