Frequency detuning properties of EDFL pulses generated by harmonic mode-locking and regenerative amplification: a comparison

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ABSTRACT

We compare the frequency detuning properties of optical pulses generated from erbium-doped fiber lasers (EDFL's) by using harmonic mode-locking and regenerative amplification techniques. The frequency detuning range of regeneratively amplified pulse (17.78 kHz) is wider than that of harmonic mode-locked pulses (7 kHz). The regeneratively amplidied EDFL pulse has a smaller pulsewidth (22 ps), a higher peak power (40.7 mW), a lower phase noise (-107 dBc/Hz at offset frequency of 100 kHz), and a lower timing jitter (0.33 ps). This is attributed to that the characteristic of the gain-switched optical pulse is remained under regenerative amplification operation. Our harmonic mode-locked erbium-doped fiber laser has a lower phase noise (-100 dBc/Hz @ offset 1 kHz; -105 dBc/Hz @ 10 kHz) than that ever reported in a regeneratively harmonic mode-locked fiber ring laser.

Keywords: Erbium-doped fiber lasers, mode-locking, regenerative amplification, frequency detuning, phase noise, timing jitter

1. INTRODUCTION

Short optical pulses can be generated either by gain switching or mode locking.[1] Gain-switched laser diodes have been extensively used to generate the picosecond optical pulses needed by high-bit-rate transmission system,[2-4] all-optical demultiplexers,[5] all-optical regenerative repeaters,[6] optical sampling systems,[7] and so on. Gain-switched lasers do not require specially fabricated devices or external cavity arrangement to generate the repetition-rate-variable pulse. In the above applications, the pulse-to-pulse timing jitter seriously degrades the bit error rate (BER) performance[8] or temporal resolution. These latter aspects are essential for applications in electro-optic probing or sampling instrumentations. However, it has been reported that active mode-locking produces pulses that are considerably more stable than those produced by gain-switched lasers. The order-of-magnitude difference in timing jitter was commonly attributed to the fundamental nature of the gain switching versus the mode-locking processes. Whereas the start up of each pulse in gain switching relies on the random generation of spontaneous photons, the start up of each pulse in mode locking is assisted by the return of the preceding pulse after a round-trip tour of the laser cavity. It was thus reasoned that gain-switched pulses suffer inherently large pulse jitter. However, Pepeljugoski *et al.* reported that the timing jitter of an actively mode-locked semiconductor laser is comparable with that of a gain-switched laser.[9] In this paper, we compare a harmonic mode-locked erbium-doped fiber laser with the regenerative amplification erbium-doped fiber laser. The latter is based on injection of a gain-switched Fabry-Perot laser pulse into a ring cavity with an erbium-doped fiber amplifier inside. The pulse shape variation under frequency detuning is observed in both configurations. The characteristics of the pulse such as the pulsewidth, the peak power, the rising time and the falling time, the phase noise, and the timing jitter in both are compared.

This paper is organized as follows. Section 2 presents the theory of frequency domain technique for characterizing the noise. Section 3 describes the various types of laser under investigation. Experimental results are then presented in Section 4.

2. THEORY OF FREQUENCY DOMAIN TECHNIQUE

For measurements of different types of pulses of erbium-doped fiber lasers (EDFL's), the frequency domain technique[10] developed by *Linde* is used for accurately calculating the timing jitter of pulses of different EDFL's. Such a method is based on shining the laser beam onto a suitable fast photodetector and then processing the detector output with an electronic spectrum analyzer to obtain the information of the power spectra of the pulses. It is shown that a wealth of

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useful information about fluctuations of the pulses can be extracted from the power spectra. Phase modulation effects, e.g., pulse "chirp", are not considered here, because the phase information is lost when the power spectra are measured. The measurement of the root-mean-square (rms) timing jitter is based on the procedure described in Ref. 10. The principle is addressed as follows. For a pulse train generated by mode-locking or regenerative amplification technique, the power spectrum of the pulse of the laser can be described as

$$P_F(\omega) = (2\pi\pi/)^2 \left|\tilde{f}(\omega)\right|^2 \sum_{\mu} \left[\delta(\omega_\mu) + P_A(\omega_\mu) + (2\pi\mu)^2 P_J(\omega_\mu)\right] \tag{1}$$

where $\omega_\mu=(\omega-2\pi\mu/T)$, and μ is an integer running from minus to plus infinity. We have used the fact that $\left|\tilde{f}(\omega)\right|^2$ is slowly varying and can be removed from the sum. Hence the power spectrum can be written as a product of an envelope $\left|\tilde{f}(\omega)\right|^2$, and a rapidly varying term given by the sum in (1).

As illustrated in Ref. 10, the sum represents a series of frequency bands centered around ω_μ with constant spacing $\Delta\omega=2\pi/T$. Each band has three different contributions. There is a δ-function contribution represented by the first term, which corresponds to the perfect, noise-free pulse train. The second term is the frequency shifted power spectrum of the amplitude noise. The third term involves the power spectrum of the random function J(t) which describes the temporal jitter. Here the jitter term is proportional to μ^2, where μ labels the individual frequency bands. The μ^2 dependence of the third term in (1) is quite significant because it permits to distinguish the two different kinds of noise and therefore to determine both $P_A(\omega)$ and $P_J(\omega)$. Because there are no contributions from the temporal jitter for $\mu=0$, the power spectrum of the amplitude noise can be directly obtained from the frequency component centered around $\omega=0$. On the other hand, the higher orders are dominated by jitter noise, and $P_J(\omega)$ can be readily determined using frequency components with $\mu>0$. When $P_A(\omega)$ and $P_J(\omega)$ are known, the amplitude fluctuations and the jitter of the laser pulses can be characterized. For example, the area of the noise spectrum of the zero frequency component ($\mu=0$) is directly related to the rms deviation ΔE of the pulse energy

$$(\Delta E/E)^2 = \left\langle A^2 \right\rangle = \int_{-\infty}^{+\infty} P_A(\omega) d\omega, \tag{2}$$

where E is the average pulse energy.

On the other hand, the rms deviation $\Delta t=<\delta^2 T>^{1/2}$ which characterizes the temporal jitter of the pulses, is directly obtained from the area of the jitter noise spectrum

$$(\Delta t/T)^2 = \left\langle J^2 \right\rangle = \int_{-\infty}^{+\infty} P_J(\omega) d\omega. \tag{3}$$

Note that ΔE and even Δt can be obtained from the truncated spectrum; determination of Δt only requires that frequency components of sufficiently high order can be measured such that the μ^2-dependence can be clearly established. This property of the power spectrum is quite remarkable. It is shown that pulse jitter less than one picosecond can be readily determined using a detector with only nanosecond time response.

3. EXPERIMENTAL SETUP

In this section, we investigate two types of erbium-doped fiber lasers (EDFL's). One is a harmonic mode-locked fiber laser (HML-EDFL) and the other is a regenerative amplification fiber laser (RA-EDFL). The driving electronics are a RF synthesizer with a 23-dB-gain RF power amplifier and the electrical pulse generator driven by an amplified sinusoidal wave for HML-EDFL and RA-EDFL, respectively.

3.1 HML-EDFL

Figure 1 is a harmonic mode-locked (HML) erbium-doped fiber laser (EDFL) by using a Mech-Zehnder intensity modulator (referred hereafter as HML-EDFL). It consists of an erbium-doped fiber amplifier (EDFA), a polarization controller (PC), a $LiNbO_3$ Mach-Zehnder intensity modulator (MZM), and a 10% output coupler. A 14.6-m-long loop of optical fiber forms the basic laser structure in which the light travels in one direction due to the isolators inside the EDFA. Light travels one round-trip of the loop is 73 ns, corresponding to a fundamental cavity response frequency of 13.73 MHz. Active harmonic mode-locking is realized by periodic modulation of the cavity loss using a MZM driven by a 27-dBm sinusoidal wave at repetition rate of around 1 GHz. The MZM is dc-biased at 5 V to operate in the linear region, thus preventing the distortion of the mode-locked pulses.

3.2 RA-EDFL

Figure 2 is the regenerative amplification (RA) EDFL (referred hereafter as RA-EDFL) by using a gain-switched Fabry-Perot laser diode (FPLD) as an optical pulse injector into a ring cavity with a gain medium (*i.e.* EDFA) inside. It consists of an EDFA, an optical circulator (OC), and a 10% output coupler. An 18.5-m-long loop of optical fiber forms the basic laser structure in which the light travels in one direction due to the isolations inside the EDFA. Light travels one round-trip of the loop in 92 ns, corresponding to a fundamental cavity response frequency of 10.82 MHz. An electrical pulse generator (*i.e.* comb generator) is employed to provide electrical pulse train at repetition rate of around 1 GHz for gain-switching the Fabry-Perot laser diode, which is dc-biased at below threshold of 12 mA (I_{th} = 13.2mA at 35 °C).

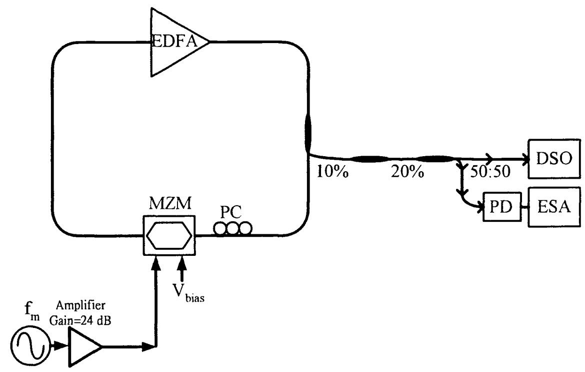

Fig. 1. The schematic diagram of harmonic mode-locked erbium-doped fiber laser (HML-EDFL). The V_{bias} is set at 5 V for linear operation. DSO: Digital sampling oscilloscope; EDFA: erbium-doped fiber amplifier; ESA: electronic spectrum analyzer; MZM: Mach-Zehnder intensity modulator; PC: Polarization controller; PD: High-speed photodetector.

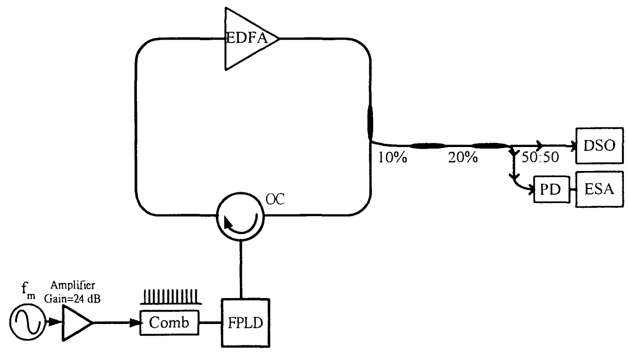

Fig. 2. The schematic diagram of regenerative amplification erbium-doped fiber laser (RA-EDFL). Comb: electrical pulse generator; DSO: Digital sampling oscilloscope; EDFA: erbium-doped fiber amplifier; ESA: electronic spectrum analyzer; FPLD: Fabry-Perot laser diode; OC: Optical circulator; PD: High-speed photodetector.

The characteristics of pulses of both configurations are measured by using a high-speed photodetector (PD, NewFocus 1014) with a digital sampling oscilloscope (DSO, Agilent 86100) and an electronic spectrum analyzer (ESA, Agilent 8565E). In HML-EDFL, for achieving harmonic mode locking, the modulation frequency needs to be matched with some harmonic of the roundtrip frequency.[10] On the other hand, for getting the best regeneratively amplified pulse train, the repetition frequency of gain-switched pulses must also match some harmonic of the roundtrip frequency. However, any tiny difference (or detuning) between the modulation frequency and the harmonic frequency of EDFL cavity could strongly affect the behavior of HML-EDFL or RA-EDFL in terms of the pulsewidth, the peak power, the 3-dB detuning bandwidth, the rising time and the falling time, the pulse shape evolution, the phase noise, and the timing jitter.

4. RESULTS AND DISCUSSIONS

In this section, we compare the relation of output power and pulsewidth versus detuning frequency, the evolution of pulse shape, absolute single sideband (SSB) phase noise spectra, and the corresponding timing jitters. Figures 3 and 4 show the output power and the pulsewidth versus frequency detuning in the HML-EDFL and RA-EDFL, respectively. At optimal condition, both configurations generated maximum output peak power of 10.8 mW (HML-EDFL) and 40.7 mW (RA-EDFL), respectively. The peak power of the latter has 3.77 times larger than that of the former. The corresponding pulsewidths are 50.7 ps (HML-EDFL) and 22 ps (RA-EDFL), respectively. It is found that in HML-

EDFL as the frequency is positive-detuned the magnitude degradation of the peak power and the pulsewidth broadening of the pulse is more serious than negative-detuned. However, in contrast with RA-EDFL the reversed situation is found. The 3-dB detuning bandwidth (defined as the doubling in pulsewidth as compared to that at zero detuning frequency) of the HML-EDFL (7 kHz) is also smaller than that of the RA-EDFL (17.78 kHz). RA-EDFL with larger 3-dB detuning bandwidth may be attributed to that the gain-switched pulse due to the superposition of the time-unmatched pulse causes pulsewidth broadening as the modulation frequency is tuned away from the optimal resonant frequency. The result implies that for keeping the quality of pulsewidth the HML-EDFL has a critical operation condition in frequency as compared with the RA-EDFL.

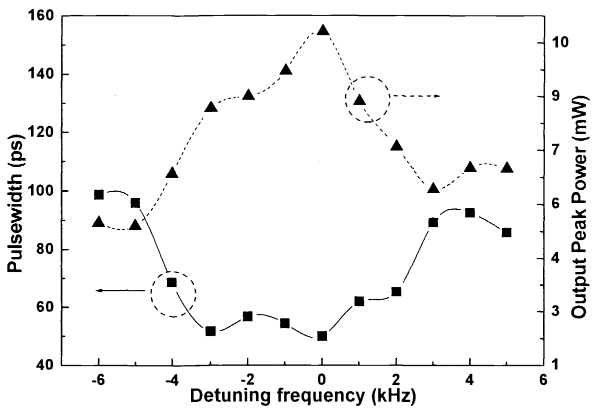

Fig. 3. The peak power (▲ dash line) and pulsewidth (■ solid line) variation as the driving frequency is detuned in the HML-EDFL configuration. The peak power pulsewidth at zero detuning frequency are 10.8 mW and 50.7 ps, respectively.

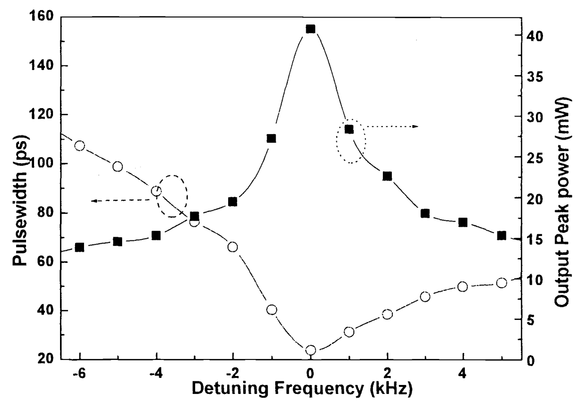

Fig. 4. The peak power (■ solid line) and pulsewidth (○ dash line) variation as the driving frequency is detuned in the RA-EDFL configuration. The peak power pulsewidth at zero detuning frequency are 40.7 mW and 22 ps, respectively.

On the other hand, the peak power of the RA-EDFL has larger decay than that of HML-EDFL as the frequency is detuned away from the optimal frequency. As the modulating frequency adjusted beyond the detuning limit, the repetition rate of the EDFL pulses dramatically changes to the higher value. As the modulation frequency is detuned away from the optimal point, it is found that the behavior of the pulse degradation is different in both configurations (see Figs. 5 and 6). In the HML-EDFL, the pulse shape is degraded seriously. By contrast, in RA-EDFL, the variation of peak power of the pulse is evident. Due to that the GSLD generates optical pulse train that circulates in the ring cavity, and the reason of evident peak power degradation may be attributed to that the unsynchronization between the injection pulse and circulating pulse. On the other hand, the HML-EDFL has a larger tolerance to generate a pulse with less power variation.

Under optimal operating condition as shown in Fig. 7, the rising time and falling time of the pulses in both configurations are analyzed. In the HML-EDFL, the rising time and falling time are 32.44 ps and 54.23 ps, respectively (Fig. 7(c)). On the other hand, the rising time and falling time of RA-EDFL are 13.33 ps and 42.81 ps, respectively (Fig. 7(a)). In addition, the rising time and falling time of RA-EDFL under open-loop condition are 14.64 ps and 30.57 ps, respectively. In comparison, the rising time and falling time of the RA-EDFL is shorter than the HML-EDFL. Noted that the peak power of RA-EDFL under close loop is enhanced by 1.72 times larger than that of open-loop RA-EDFL. The phase noise of optical pulses generated from HML-EDFL and RA-EDFL configurations are also characterized using a frequency domain technique which has been widely used to quantify optical pulse noise[10,12-15]. In Fig. 8, it is clearly found that in HML-EDFL the absolute SSB phase noise density (trace (a)) is larger than that in RA-EDFL (trace (c)) by 3 dB at offset frequency ranged between 1 kHz to 1 MHz. The phase noises of HML-EDFL and RA-EDFL at offset frequency of 100 kHz are -104 and -107 dBc/Hz, respectively. The HML-EDFL has a lower phase noise (-100 dBc/Hz @ offset 1 kHz; -105 dBc/Hz @ 10 kHz) than that ever reported in a regeneratively harmonic mode-locked fiber ring laser.[16] The spikes in the band 10 Hz-1 kHz are noise signals from the fluorescent lamp. Trace (d) is the phase noise of the electrical pulse train for gain-switching the FPLD. Trace (e) is the phase noise of the driving electronics (*i.e.* frequency synthesizer) as the baseline of the measurement.

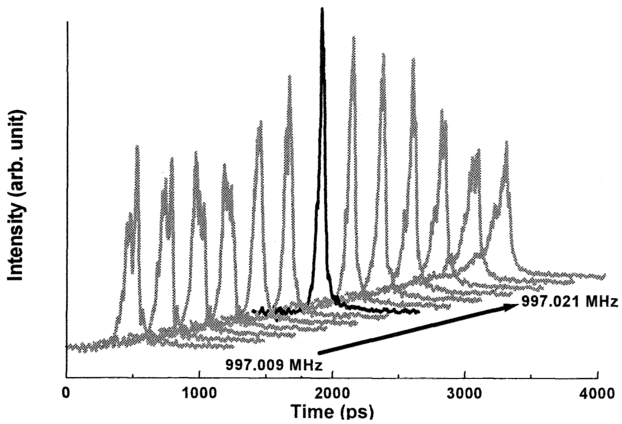

Fig. 5. The variation of pulse shape as the driving frequency is detuned in the HML-EDFL configuration.

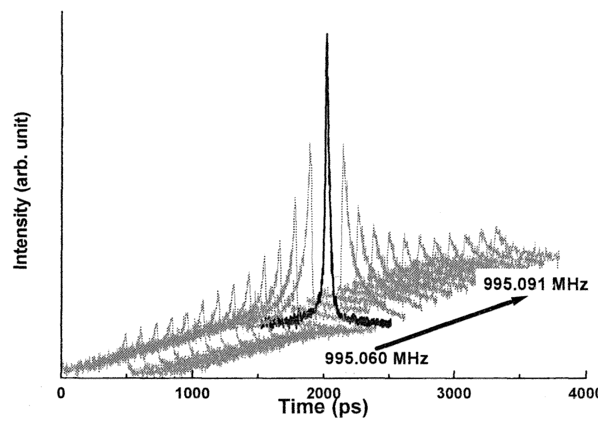

Fig. 6. The variation of pulse shape as the driving frequency is detuned in the GSLD-EDFL configuration.

In addition, RA-EDFL under open loop is shown in trace (b), which is a little higher than that under close loop. It is attributed to the light injection into FPLD causes the noise reduction of pulses. By subtracting the SSB phase noise spectrum at harmonic frequency with that at fundamental frequency of the EDFL pulses, the rms timing jitter σ in a bandwidth extending from f_L to f_H is given by

$$\sigma = \frac{1}{2\pi f_0}\sqrt{2\int_{f_L}^{f_H}\left[\left(10^{L_n(f)/10} - 10^{L_1(f)/10}\right)/\left(n^2 - 1\right)\right]df} \tag{4}$$

where f_L and f_H are integration boundaries; $L_1(f)$ and $L_n(f)$ are phase noise power spectrum densities of fundamental an *n*-th harmonic signals, respectively; n is harmonic number; f_0 is the repetition frequency of the laser pulse. The rms timing jitters of both (in the band 10 Hz to 100 kHz) are calculated by (4).[10]

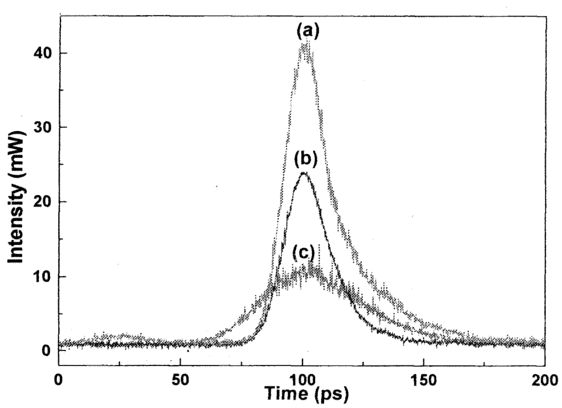

Fig. 7. The pulsewidth under optimal operating condition. (a) the peak power of RA-EDFL pulse (close loop) is 40.7 mW (b) the peak power of RA-EDFL pulse (open loop) is 23.8 mW (c) the peak power of HML-EDFL pulse is 11 mW.

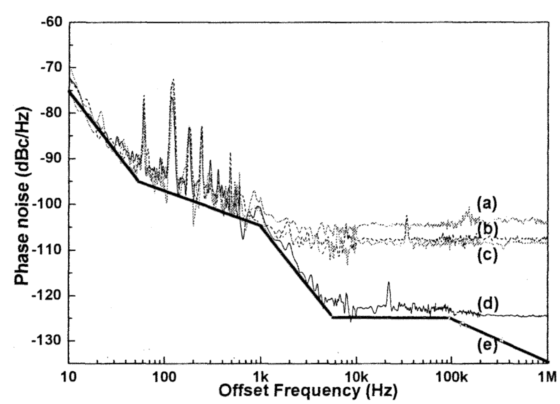

Fig. 8. The absolute single sideband phase noise density in both configurations. The estimated frequency ranged from 10 Hz to 1 MHz. (a) HML-EDFL (b) RA-EDFL (open loop) (c) RA-EDFL (close loop) (d) electrical pulse (e) driving electronics

The HML-EDFL has the rms timing jitter of 0.49 ps in the band 10 Hz-100 kHz and the GSLD-EDFL has the rms timing jitter of 0.33 ps in the same band. According to measured results, the HML-EDFL is more unsuitable than the RA-EDFL for electro-optic sampling systems or high-speed TDM applications. It is noted that both configurations didn't adopt any scheme of cavity stabilization.

5. CONCLUSIONS

This paper has dealt with a comparison between a harmonic mode-locked erbium-doped fiber laser (HML-EDFL) and a regenerative amplification erbium-doped fiber laser (RA-EDFL). The results show that for an electro-optic sampling application a RA-EDFL has better performance in the pulsewidth, the peak power, the 3-dB detuning bandwidth, the rising time and falling time, the phase noise, and the timing jitter. These results are summarized in Table I. Although the regenerative amplification technique can enhance the peak power of the gain-switched pulse by 1.72 times whereas the characteristic of continuous-repetition pulse of the gain-switched laser is broken due to insertion of the ring cavity. However, by using such a technique a high power, short pulsewith, and low timing jitter source can be readily obtained merely using a Fabry-Perot laser diode and erbium-doped fiber laser to construct a regenerative amplification EDFL.

TABLE I

	HML-EDFL	**RA-EDFL**
Pulsewidth	50.7 ps	22 ps
Peak power	10.8 mW	40.7 mW
3-dB detuning bandwidth (The frequency range as pulsewidth doubling as compared to that at zero detuning frequency)	7 kHz	17.78 kHz
Rising time ($\tau_{10\%}$ **to** $\tau_{90\%}$)	32.44 ps	13.33 ps
Falling time ($\tau_{90\%}$ **to** $\tau_{10\%}$)	54.23 ps	42.81 ps
Absolute SSB phase noise density (At frequency offset ranged from 10 Hz to 100 kHz)	-104 dBc/Hz (offset @ 100 kHz)	-107 dBc/Hz (offset @ 100 kHz)
Timing jitter (Integration range from 10 Hz to 100 kHz)	0.49 ps	0.33 ps

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