High-Resolution Diode Laser Spectrometer for the Ca $^1S_0$-$^3P_1$ Transition

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ABSTRACT

A diode laser spectrometer in the visible range was developed. To achieve narrow linewidth and high power, a master-laser/slave system was employed. High-resolution spectroscopy of the $^1S_0$-$^3P_1$ transition of Ca was performed and optical Ramsey fringes were observed with a resolution of below 36 kHz using a thermal atomic beam.

Keywords: extended cavity diode laser, linewidth reduction, optical frequency standard
optical Ramsey resonance, injection lock, Ca

1. INTRODUCTION

The $^1S_0$-$^3P_1$ intercombination transition of Ca at 657 nm has been extensively studied, primarily owing to its potential as an optical frequency standard[1-3]. Most of the studies have been conducted with dye lasers.[4] The frequency of a dye laser was stabilized to the Ca transition with a precision of 6×10^{-12} using the Ramsey fringe technique.[5] Recently, the separated field excitation geometry used in the optical Ramsey technique has attracted much attention as a method to realize an atom interferometer.[6]

The development of tunable laser diodes in the visible range provided the possibility of using diode lasers as an alternative to dye lasers. Besides being compact and inexpensive, laser diodes are capable of long term operation, ensuring a reliable light source. Furthermore, by the advent of high power diode lasers, power comparable to dye lasers has become available at some wavelengths. These features strongly suggest that dye lasers will be replaced by laser diodes in this application. However, the diode laser's linewidth has to be substantially reduced. Remarkable linewidth reduction has been demonstrated for infrared AlGaAs laser diodes by negative electrical feedback[7] or optical feedback [8]. These methods, however, do not work as effectively for visible InGaAlP diode lasers[9], because of their large linewidth

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or relaxation oscillations. It is possible, when the output facet of the laser diode is anti-reflection (AR) coated, to obtain a linewidth of less than 100 kHz by using an extended cavity configuration.[10] Modest electrical feedback bandwidths may then be used for further linewidth reduction. By feedback to an internal phase modulator[11] or the injection current[12], significant linewidth reduction of extended cavity diode lasers (ECDL) has been achieved. In the extended cavity configuration, more stable operation is obtained by increasing the optical feedback from the grating, As a result, lower output is available from an ECDL compared to a solitary diode laser. The output power may be enough for the spectroscopy of laser cooled atoms[13] or absorption spectroscopy in a cell[14], but is often not enough for the optimum high resolution spectroscopy of a thermal atomic beam. However, only a small amount of power is required to injection lock a second diode laser.[15] By injection locking one or more diode lasers, adequate power is easily obtained.

For the purpose of high-resolution spectroscopy of the Ca $^1S_0$-$^3P_1$ transition, we stabilized the frequency of an ECDL using a high finesse optical cavity. To obtain more power, the output of the ECDL was used to injection lock a second diode laser. In this paper, we describe our diode laser system and experiments with optical Ramsey resonances in the atomic beam.

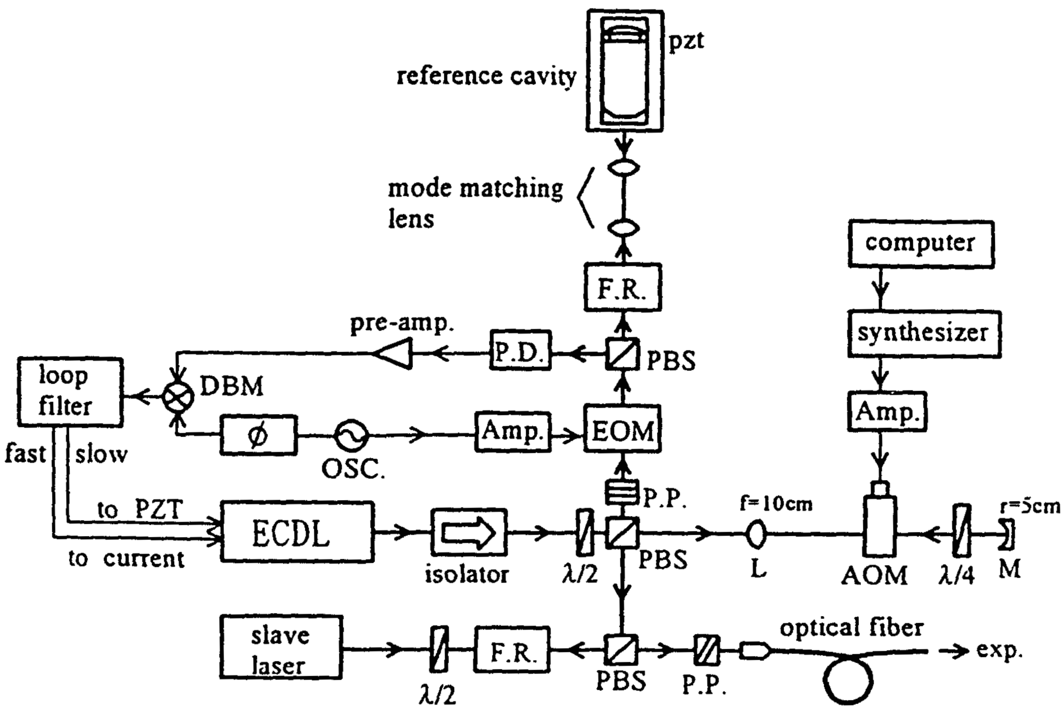


Figure 1 Schematic diagram of the diode laser spectrometer. Shown is the frequency stabilized extended cavity diode laser (ECDL) with the slave laser used for power amplifier. See text for details. L:lens, M:mirror, PP:anamorphic prism pair, FR:Faraday rotator, PD:photo diode, ϕ :phase shifter.

2. DESIGN OF A DIODE LASER SPECTROMETER

Figure 1 shows the configuration of our diode laser spectrometer, where a master-laser/slave system is employed. The output of the ECDL (the master laser) was divided into two beams by a polarization beam splitter, which in conjunction with a half wave plate acted as a variable beam splitter. One of the beams with a power of approximately 300 μW was used for frequency locking of the ECDL to a reference cavity, which had a PZT. The other beam with approximately 1 mW passed an acousto-optic modulator (AOM) twice and then was injected into a slave laser. The effect of a slight shift of the AOM output beam (caused by imperfect alignment through the AOM) was minimized by choosing this beam as the injection beam. The AOM was driven by a synthesizer with the center frequency of 100 MHz, and fine frequency tuning over 2 MHz was controlled by a computer. The PZT in the reference cavity provided the coarse tuning. The output of the slave laser passed an anamorphic prism pair and was coupled into a polarization preserving optical fiber. Intensity fluctuation after the fiber was less than 1 %, thus requiring no active power stabilization. The optical fiber served to improve the spatial mode, as well as to send the laser light to the Ca beam vacuum chamber. About 3 mW was available after the fiber.

2.1 Configuration of the extended cavity diode laser

Figure 2 shows the configuration of the ECDL used in our experiment. The laser was mounted on a aluminum plate and enclosed in a box made of rubber foam. The ECDL consisted of an AR coated laser diode (Toshiba, TOLD9421, P=5 mW)[16] operating near 650 nm, a collimating lens(N.A=0.55, f=3.9 mm), a holographic grating (2400 grooves/mm) and a PZT driven mirror attached to a precision mount. The grating was utilized in a grazing incidence configuration, because the direction of the output beam is not affected by tuning and maximum resolution and highest diffraction efficiency are achieved simultaneously. The beam from the laser diode illuminated an 8 mm wide region of the grating across the grooves with the incident angle of 80°. The 0th and 1st order diffraction efficiencies were 22 % and 60 %,

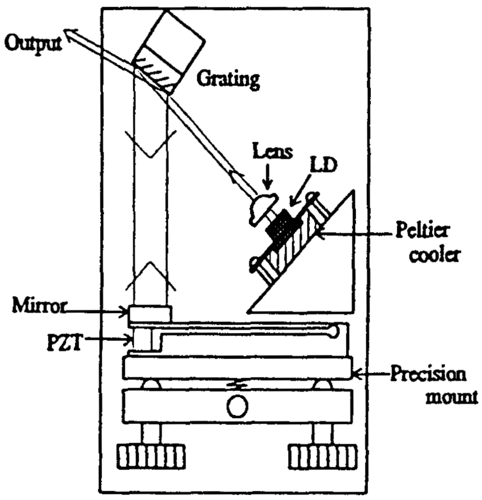


Figure 2 Configuration of the extended cavity diode laser.

respectively. The extended cavity length was 10 cm, corresponding to a longitudinal mode spacing of 1.5 GHz. The threshold current of the solitary laser diode before and after AR coating was 59 mA and 80 mA, respectively. Operating in an ECDL mode, the injection current was typically 90 mA with the output power of 1.5 mW. The temperature was carefully tuned to obtain stable single mode oscillation. By changing the voltage applied to the PZT on which the mirror was attached through a simple aluminum flexure, the frequency could be tuned over 2 GHz without mode hopping. This tuning range was limited by the PZT voltage supply($V=\pm 15V$).

2.2 Frequency stabilization of an extended cavity diode laser

Extended cavity length of 10 cm resulted in a short term linewidth of approximately 30 kHz, which is additionally broadened by low frequency vibration and acoustics. Sharp reduction of this linewidth is achieved by the suppression of the frequency fluctuations below 100 kHz. To reduce the frequency fluctuation of the ECDL, we locked its frequency to a high finesse optical cavity[17] using the rf heterodyne set-up shown in Fig.1. Employing an external electro-optic modulator (EOM), sidebands were added to the laser frequency without noticeable amplitude modulation. The modulation frequency was 15 MHz. Driving the EOM with a rf power of 1 W generated sidebands having 5 % of the total power. An anamorphic prism pair was used to obtain a small circular beam shape so that the beam could pass the 2 mm apertures of the EOM and the Faraday rotator. The reference cavity was a non-confocal cavity, which had a linewidth of 300 kHz (FWHM) and a 1.5 GHz free spectral range. It was constructed from a ULE glass rod on which two mirrors with the curvature of 1 m were attached by magnets. A PZT for tuning was mounted between one of the mirrors and the glass rod. The cavity was mounted inside a vacuum housing to reduce the index fluctuation and acoustic noise. In the current experiment, no special care was taken for the vacuum housing with regard to thermal and acoustic insulation. We put the reference cavity on the sand in an aluminum bed in an attempt to avoid vibration.

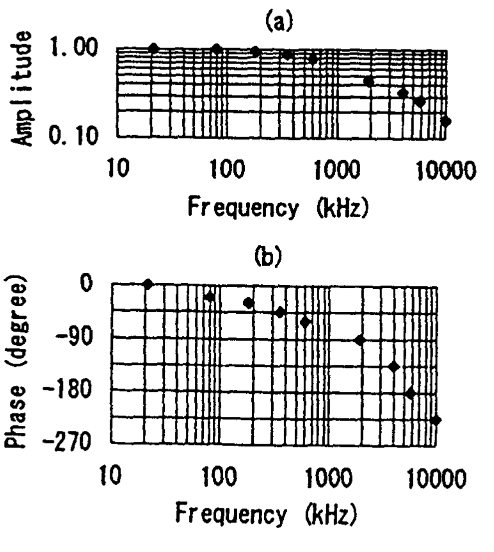


Figure 3 Current-frequency transfer function of the ECDL.

The light reflected from the cavity was detected by a fast photodiode (bandwidth = 25 MHz). The resulting photo current was amplified and phase sensitively detected by a double balanced mixer to provide an error signal. The fast component of the error signal was added to the injection current through ac-coupling and the slow component was fedback to the PZT. The slow feedback loop, whose bandwidth was limited by mechanical resonance of the PZT (~13 kHz), served to reduce the dynamic range required for the current feedback loop. In order to check the control bandwidth of the faster feedback loop, we measured the current-frequency transfer function of the ECDL. Figure 3 shows the frequency modulation characteristics of the ECDL. The response of the amplitude is nearly flat over 1 MHz. The phase lag reaches 90° at 1.9 MHz and 180° at 5.8 MHz. These results ensure a bandwidth sufficient for significant linewidth reduction.

When used in the reflection mode, the frequency response of the cavity decreases in a 1/f fashion above the Fourier frequency of the linewidth (~300 kHz). The 1/f roll-off of the cavity was compensated by the servo electronics. The faster loop had approximately 140 dB of gain at 50 Hz, which was then rolled-off with double-pole and single-pole sections to a unity gain frequency of ~1.3 MHz.

The analysis of the error signal showed that the linewidth of the ECDL was reduced to sub-kHz level relative to the reference cavity. However, the absolute laser linewidth is broadened by the mechanical jitter of the reference cavity. We examined the resolution of the laser system by directly probing the very narrow transition of Ca as described in section 3.

2.3 Injection locking of visible diode lasers

Injection locking is a powerful technique to transfer the frequency and the spectral purity of a master laser to a slave laser. We tried injection locking for three kinds of visible diode lasers, TOLD 9421 (from Toshiba, P=5 mW), CQL820/D (from Phillips, P=5 mW) and an AR coated TOLD 9421.[16] The TOLD 9421 and CQL820/D lasers had a linewidth of approximately 60 MHz, which was measured by a scanning Fabry-Perot interferometer with the linewidth of 10 MHz. In the experiment, the master laser was the linewidth narrowed ECDL oscillating at 657 nm. The slave lasers were operated around 654 nm (free running) with an output power of 5 mW. In order to lock the uncoated TOLD 9421, approximately 200 μW of input was required. The locking range was only a few hundred MHz, which in comparison to infra-red diode lasers is approximately one order of magnitude smaller for the same injection power. The performance of the CQL820/D was closer to that of the infra-red laser diodes. About 70 μW of input could lock the CQL820/D with the locking range of 2 GHz. The best result was obtained with the AR coated TOLD 9421. Below threshold, this laser is expected to act as a power amplifier. When there was no input, the output power of the AR coated TOLD 9421 increased gradually with the injection current as shown by the curve (a) in Fig. 4. When there was an input, the frequency of this laser was locked to the master laser irrespective of the frequency, showing no definite locking range. In Figure 4, the output power P_{out} of the slave laser is plotted as a function of the slave injection current I for several input powers P_{in} . Figure 5 shows the output power dependence on the input power. When the temperature of the slave laser was scanned, the output power changed periodically by approximately 30 %. However, the oscillation frequency was always the same as the master laser (as confirmed by the presence of a beat note, see below).

Because of the ease of operation, the AR coated TOLD 9421 was used as a slave laser in the system. The operating conditions were typically, P_{in}=500 μW, P_{out}=8 mW, I=97 mA. In order to check that the slave laser adopted the linewidth of the master laser, we measured a beatnote between the master laser and the slave laser, whose frequency was 200 MHz shifted from the master laser by an AOM. As the AOM was driven by the output of the synthesizer, it did not contribute to the linewidth of the beat signal. Figure 6 shows the beat signal centered at 200 MHz. The small peaks located at 200 Hz and 1.9 kHz apart from the main peak are due to the mechanical vibration in the system. The linewidth of the beat signal was less than 30 Hz, limited by the resolution of the spectrum analyzer. From this result, we infer that most of the slave power is well phase locked to the master laser.

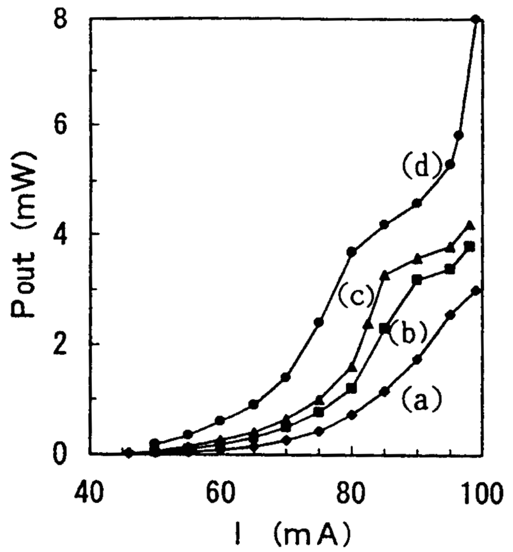


Figure 4 Output power P_{out} of the slave laser as a function of injection current I measured at several input power P_{in} of (a) 0 μW ,(b) 100 μW, (c) 200 μW and (d) 500 μW.

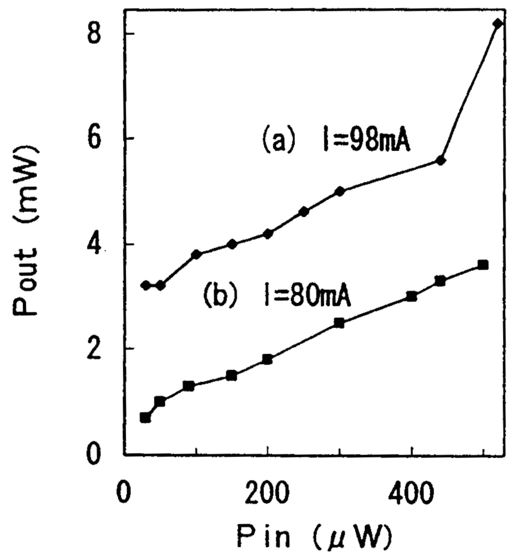
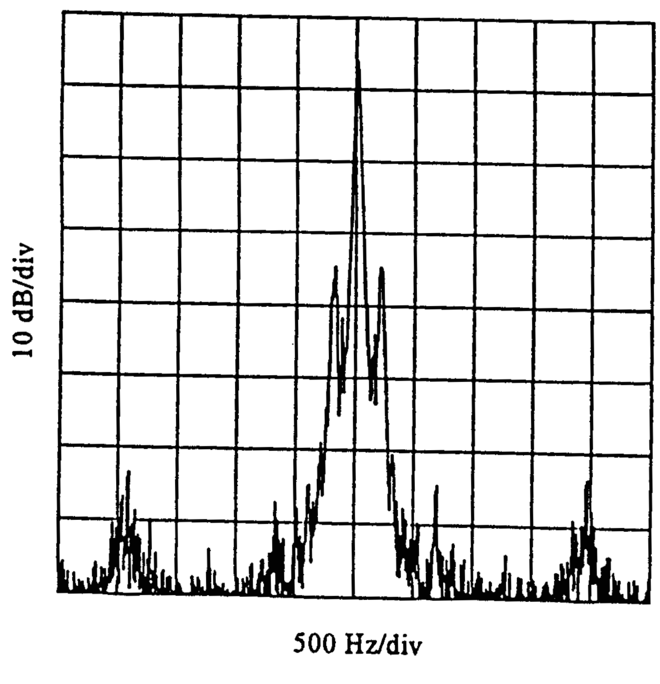


Figure 5 Output power P_{out} of the slave laser as a function of input P_{in} measured with the injection current $I$of (a) 80 mA and (b) 98 mA.

Figure 6 Beat signal between the master laser and the slave laser.
The frequency of slave laser is 200 MHz shifted from the master laser by an AOM.



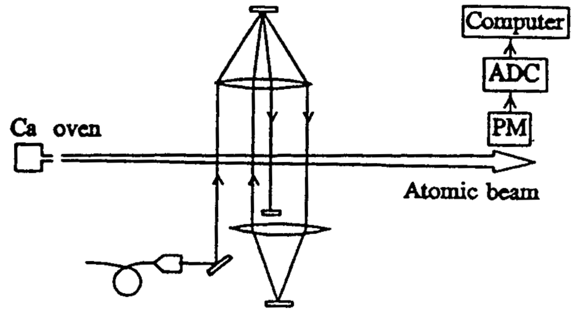


Fig.7 Experimental setup of the optical Ramsey resonance on a Ca atomic beam.

3. SPECTROSCOPY

To evaluate the performance of the diode laser spectrometer, the Ca intercombination line was probed using the four beam Optical Ramsey technique. Figure 7 shows a schematic of the experimental set up. The Ca oven at a temperature of 700℃ produced an atomic beam with the most probable velocity of u=780 m/s. The laser light from the optical fiber was collimated to a beam 0.5 mm in diameter and introduced into the vacuum chamber. The beam was retro-reflected by two "cat's eyes" to form two counter-propagating pairs of travelling waves having a separation D. In order to excite the field insensitive m=0→m=0 transition, a transverse magnetic field was applied to the atomic beam and the laser polarization was aligned parallel to the field by a λ/2-plate. The laser power was typically 2.5 mW, because this power gave the best fringe contrast. Ramsey fringes were obtained by scanning the synthesizer which drove the AOM and monitoring the fluorescence intensity 20 cm downstream from the excitation zone. Before scanning, the reference cavity was tuned to the center of the Ca transition. Figure 8 shows the Ramsey fringes observed at different beam separations, (a) 2D=10 mm and (b) 2D=21 mm.

In this conventional optical Ramsey technique, the signal is a superposition of two recoil components separated by $\delta\nu=hk^2/m$=23.1 kHz. In Fig. 8(a), the two recoil components overlap and result in a single peak with a linewidth of 36 kHz. In Fig. 8(b) the two components with a linewidth of 18 kHz are resolved, but with decreased S/N ratio. The higher frequency part of the signal is distorted by the drift of the PZT. In the optical Ramsey resonance, the linewidth $\Delta\nu$ (FWHM) of each component is approximately given by $\Delta\nu=u/4D$, which is (a) 20 kHz and (b) 10 kHz. The laser linewidth does not contribute to the fringe linewidth but becomes a factor to reduce the fringe contrast. Since the laser beam from the optical fiber had a Gaussian profile and was well collimated, the effect of wavefront curvature is very small. Therefore, we believe that the decrease of the S/N ratio at high resolution is a consequence of the residual jitter of the reference cavity due to insufficient damping. In the present experiment, the circumstance of the cavity is far from optimum; the reference cavity has a PZT and two rotary pumps used to evacuated the Ca beam chamber generated acoustics and vibrations. We expect to obtain better S/N ratio at higher resolution by

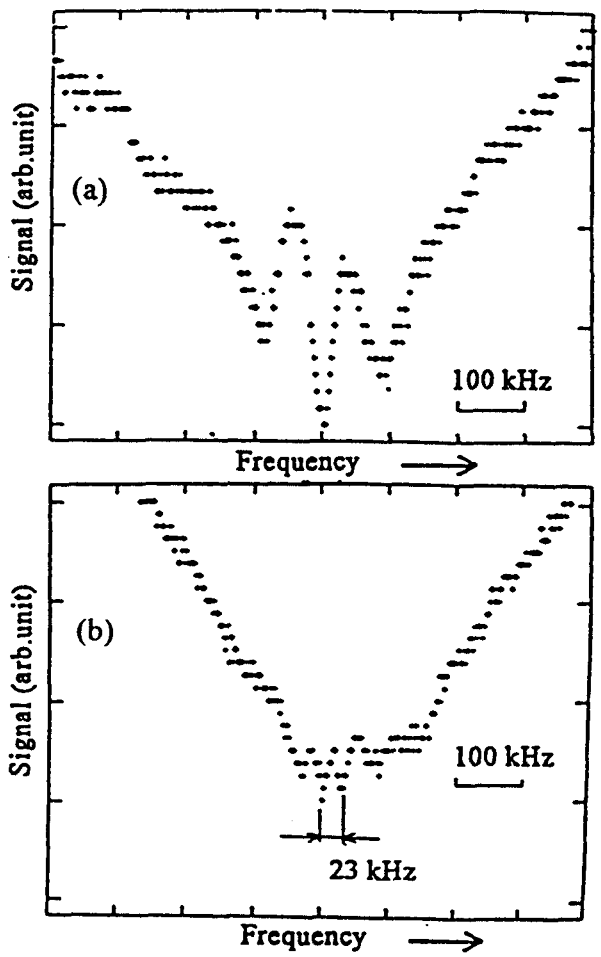


Figure 8 Optical Ramsey fringes obtained at the beam separations of (a) 2D=10 mm and (b) 2D=21 mm.

improving the damping of the vibration and using a reference cavity without a PZT to avoid drift.

4. CONCLUSIONS

A high-resolution diode laser spectrometer in the visible region has been described. This system produces 3 mW in a Gaussian beam and is available for various experiments, including optical frequency/ length standards and atom interferometers. Optical Ramsey resonance was performed on the $^1S_0$-$^3P_1$ transition of Ca and linewidths of less than 36 kHz were observed. The resolution of the present system is believed to be limited by the stability of the reference cavity. The cavity has a tuning PZT and is placed on a sand bed instead of being suspended by the wires. By improving the reference cavity mounting, higher resolution is expected.

We are now constructing a second cavity, which is suspended and has no tuning PZT. When this cavity is used in the system, the frequency discrepancy between the cavity and the atom has to be compensated. One method is to use an offset-lock laser.[18] A second approach is to use a wide band EOM or several AOM's.

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