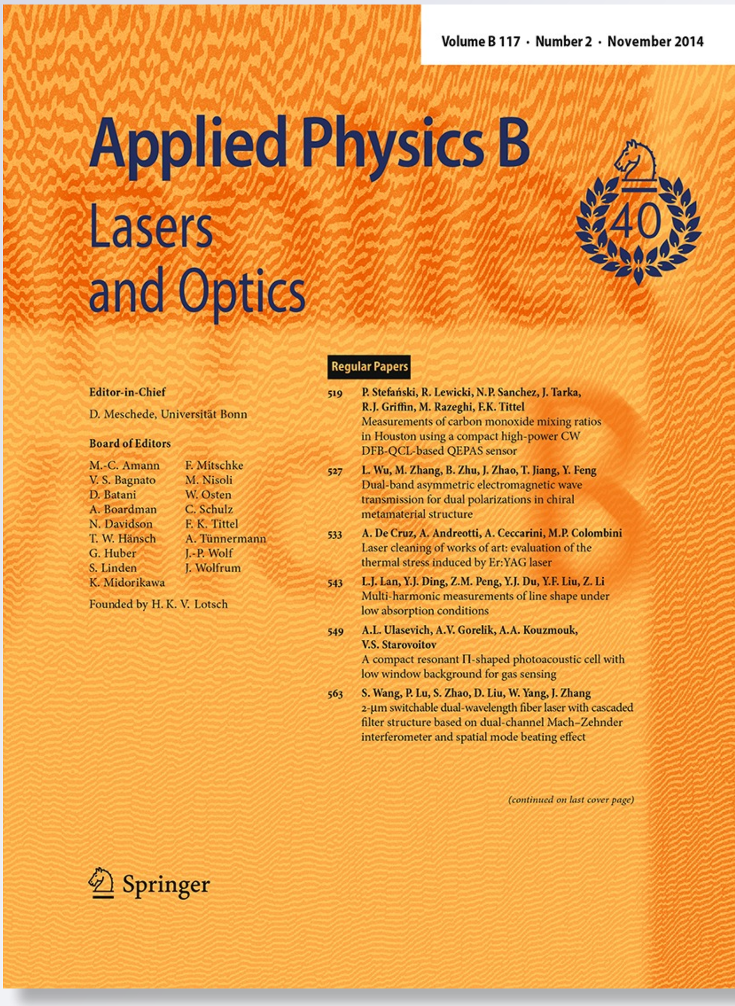
Dual Ti:sapphire comb lasers by a fiber laser pumping scheme and a hand-sized optical frequency reference

Tze-Wei Liu, Chien-Ming Wu, Yen-Chu Hsu & Wang-Yau Cheng

Applied Physics B
Lasers and Optics

ISSN 0946-2171
Volume 117
Number 2

Appl. Phys. B (2014) 117:699-705
DOI 10.1007/s00340-014-5885-z



Volume B 117 · Number 2 · November 2014

Applied Physics B
Lasers and Optics

40

Editor-in-Chief
D. Meschede, Universität Bonn

Board of Editors
M.-C. Amann, V. S. Bagnato, D. Batani, A. Boardman, N. Davidson, T. W. Hänsch, G. Huber, S. Linden, K. Midorikawa, F. Mitschke, M. Nisoli, W. Osten, C. Schulz, F. K. Tittel, A. Tünnermann, J.-P. Wolf, J. Wolfrum

Founded by H. K. V. Lotsch

Regular Papers

519 P. Stefański, R. Lewicki, N.P. Sanchez, J. Tarka, R.J. Griffin, M. Razeghi, F.K. Tittel
Measurements of carbon monoxide mixing ratios in Houston using a compact high-power CW DFB-QCL-based QEPAS sensor

527 L. Wu, M. Zhang, B. Zhu, J. Zhao, T. Jiang, Y. Feng
Dual-band asymmetric electromagnetic wave transmission for dual polarizations in chiral metamaterial structure

533 A. De Cruz, A. Andreotti, A. Ceccarini, M.P. Colombini
Laser cleaning of works of art: evaluation of the thermal stress induced by Er:YAG laser

543 L.J. Lan, Y.J. Ding, Z.M. Peng, Y.J. Du, Y.F. Liu, Z. Li
Multi-harmonic measurements of line shape under low absorption conditions

549 A.L. Ulasevich, A.V. Gorelik, A.A. Kouzmouk, V.S. Starovoitov
A compact resonant Π-shaped photoacoustic cell with low window background for gas sensing

563 S. Wang, P. Lu, S. Zhao, D. Liu, W. Yang, J. Zhang
2-μm switchable dual-wavelength fiber laser with cascaded filter structure based on dual-channel Mach–Zehnder interferometer and spatial mode beating effect

(continued on last cover page)

Springer

Springer

Appl. Phys. B (2014) 117:699–705
DOI 10.1007/s00340-014-5885-z

Applied Physics B
Lasers and Optics

Dual Ti:sapphire comb lasers by a fiber laser pumping scheme and a hand-sized optical frequency reference

Tze-Wei Liu · Chien-Ming Wu · Yen-Chu Hsu · Wang-Yau Cheng

Received: 11 December 2013 / Accepted: 17 June 2014 / Published online: 2 July 2014

Abstract A dual-comb laser system containing two femtosecond Ti:sapphire (Ti:S) lasers is reported, in which the ultrashort pulses are pumped by one common fiber laser and the influences of the different pumping noise are presented both in time-domain and frequency-domain. In addition, the dimensions of dual Ti:S comb system are reduced due to the implementation of one hand-sized optical frequency reference, from which the needed space and cost for two "self-reference" optics are saved.

1 Introduction

Dual-comb laser systems, which consist of two mutually coherent frequency comb generators of slightly different repetition frequencies, have shown to be promising devices for interferometric measurements, such as optical coherence tomography [1] or multiheterodyne Fourier transform spectroscopy [2]. High-precision absorption and dispersion molecular spectra [3, 4] were demonstrated with such systems. Nowadays, the dual-comb laser system is the most versatile light source in terms of being able to rapidly resolve molecule spectra with simultaneously broadband and high resolution. The high peak power of the comb laser, compared with the continuous wave (CW) laser, further benefits the search for nonlinear spectra [5]. The Ti:sapphire (Ti:S) comb laser is among the most popular comb lasers and plays an important role in the wavelength region from near infrared (NIR) to extreme-ultraviolet (XUV) by additional high-harmonic generation (HHG) [6] [7]. Yet, the cost and inconvenience of the Ti:S comb laser limit its applications further to the interdisciplinary fields [8] and are believed to be the main reasons that only one dual Ti:S comb-based molecule spectra was demonstrated in the literature, to our knowledge [9]. The Ti:S comb laser involves a complicated pumping scheme and a sensitive "self-reference" scheme [10]. Two scenarios to eliminate these two drawbacks are proposed and demonstrated in this report: One is to replace the conventional pumping scheme, in which the scheme needs a cavity control for enhancing the power of fundamental light; the second is to replace the "self-reference" scheme, in which the scheme requires a very sensitive light coupling for feeding a laser beam into a microstructured fiber.

To simplify the pumping source, we implement a fiber laser without the aforementioned "cavity scheme". Thanks to the invention of the high-MgO-doped periodically poled stoichiometric $LiTaO_3$ (MgO:sPPLT) that is high photorefractive damage threshold [11], we are able to produce stable green radiation for simultaneously pumping two Ti:S lasers with only one $LiTaO_3$ crystal. This work was previously demonstrated in 2009 by Samanta et al. [11] whose work showed the flexibility of pumping CW Ti:S laser by fiber laser. However, a mode-locked laser needs more rigorous condition of pumping laser and the successful pumping by fiber laser was not reported in the literature, to our knowledge. In particular, we need to know more about the influences on the laser mode quality, repetition rate jitter, and pulse chirping for upgrading the fiber laser-pumped mode-locked lasers to a dual-comb system. In this report, we are the first to show that the single-fiber laser-

T.-W. Liu · C.-M. Wu · W.-Y. Cheng (✉)
Department of Physics, National Central University, No. 300, Jhongda Rd., Jhongli City 32001, Taoyuan County, Taiwan
e-mail: wycheng@ncu.edu.tw

T.-W. Liu · Y.-C. Hsu
Institute of Atomic and Molecular Science, Academia Sinica, Taipei, Taiwan

based pumping scheme can be used for building two comb lasers under the criterion of low power ripples.

To overcome the inconvenience of the self-reference scheme, we implemented a hand-sized optical frequency reference of which the frequency is stabilized to cesium atom 6S-8S Doppler-free hyperfine transition [12] at 822-nm wavelength. Recently, the absolute frequency of the aforementioned transition was very carefully measured by Wu et al. [13]. Locking the frequency of comb mode directly to some transitions of atom, ion, or molecule has been performed in many experiments [14], in which complicate schemes (relative to our scheme) were used [4, 15–20]. On the other hand, the intracavity diode laser with the frequency stabilized to Cs two-photon transition is able to have the dimensions of hand size and was first realized at the year of 2011 by Chen et al. [12].

2 Experimental Setup and Result

The schematic diagram of our experimental setup is shown in Fig. 1. The single-mode fiber laser (fiber laser A, [21]) could yield maximum power of 30 W at a 1,064-nm wavelength with a 2 % power ripple (100 kHz bandwidth). The beam waist on the center of second harmonic generator (SHG, 3-cm-long MgO:sPPLT [22]) is 30 µm and that produces a 9.3 Watt green radiation with a proper crystal temperature (48 ± 0.002 °C). After the collimating lens f_4 (f = 10 cm), the green radiation is divided into two different optical paths, and two acoustic-optical modulators (AOM1, AOM2) are implemented for controlling the pumping powers to control the offset of two comb lasers [23]. The two Ti:S lasers were modified from Gigaoptics tunable GTW [24] with their prisms removed, since we found that the original design has the drawback of orthogonal control between mode frequency and repetition rate. Both comb lasers have the emitting spectra centered at 822-nm wavelength and 50 femtosecond pulse durations and around 1 GHz repetition rate. The difference of repetition rate (Δf_r) could be set at several of ten MHz to several MHz. We randomly chose Δf_r to be 4 MHz for some demonstrations in this paper. The two Ti:S resonators share the same cooling base in order to reject common noises in the dual-comb experiments, since the difference of repetition rates could cancel out the common rep.-rate noises that arise from two laser resonators.

Figure 2 illustrates how our "common-base, common light source" structure rules out the common drift of two repetition rates. We recorded the free-run repetition rates of two lasers for 3 h and find both repetition rates drift 1.8 MHz, as shown in Fig. 2a. The difference of two repetition rates (Δf_r) is displayed in Fig. 2b and in that the 3 h drift of Δf_r is almost unobservable, while the peak-to-peak fluctuation is around 1 kHz at 1 s data averaging time. Therefore, our "common-base" structure offers a relatively quiet noise background in terms of the applications on dual-comb spectroscopy, particularly in those experiments for which the repetition rates were not necessary to be rigorously locked [25, 26].

The electronic part of our experimental setup is illustrated by the dashed inset of Fig. 1. The repetition rates are controlled by two different synthesizers [27] (not shown in Fig. 1) whose time bases are phase-locked to each other. The two Ti:S laser outputs are sent to beat against the same cesium two-photon stabilized diode laser (Ref. Laser) that results in two different beatnotes, that is, $f_{comb\ \#1}-f_{ref}$ and

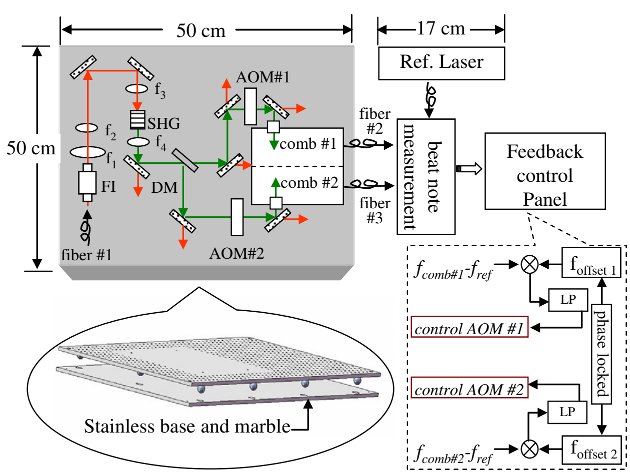


Fig. 1 Schematic diagram of our dual-comb laser systems. FI: Faraday Isolator; SHG: second harmonic generator; DM: Dichromatic mirror; Ref. Laser: the cesium two-photon stabilized diode laser (reference laser) [12]; LP: low-pass filter; $f_{comb\ \#1(\#2)}-f_{ref}$: the beat note between the frequency of one comb mode and the reference laser. $f_{offest\ 1(2)}$: Stable RF synthesizer for providing comb laser offset frequency

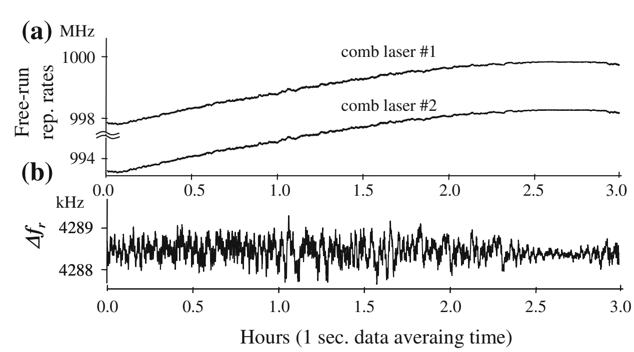


Fig. 2 Cancellation of the common drift of the repetition (rep.) rates in our common-base structure, in which both of the mode-lock lasers are in free-run and the data are recorded with one second data averaging time. **a** 3 h measurement of the two rep. rates in which both of them drift for 1.8 MHz. **b** the difference of two rep. rates (Δf_r) in which the drift of Δf_r is almost unobservable

$f_{\text{comb \#2}}{-}f_{\text{ref}}$ in Fig. 1. The two beatnotes are frequency stabilized by two stable frequency sources, namely, $f_{\text{offset 1}}$ and $f_{\text{offset 2}}$ [28]. The reference laser is a cesium 6S-8S 822-nm two-photon stabilized diode laser with an intra-cavity scheme, of which the dimensions are measured as small as 17-cm long, 7-cm wide, and 5-cm high [12]. The output frequency of our optical reference is modulated at 4-MHz modulation width so that one can retrieve the first-derivative error signal via the detection of 7P-6S fluorescence, with the assistance of a PMT (photon multiplier tube) and a home-built lock-in amplifier.

Fiber #1 in Fig. 1 can be disconnected from the whole pumping optics, contributing to the mobility of the dual-comb system. The entire optics of the dual-comb laser system had once been moved 49.8 km after fiber #1 was disconnected. After re-connecting fiber #1, we found that a trace of the pump beam starting from the Faraday isolator (FI) to each Ti:S crystal was almost unchanged, and a stable mode-locking still remained.

2.1 The influence of different pump lasers

We alternate pumping sources to compare the frequency performances of the Ti:S oscillator, in which the same Ti:S oscillator is used. The frequency performances we discuss in this report are the linewidth of both repetition rate and laser mode that affect the resolution of dual-comb spectroscopy mostly. In this section, we label the two fiber lasers as fiber laser A [21] and fiber laser B [29] and label the diode laser-pumped solid-state laser as DPSS laser [30]. We find that the DPSS-pumping source yields almost the same frequency performances as that pumped by fiber laser A, but consumes nearly three times more electric power at 10 W green radiation. Therefore, we focus on the comparison between fiber laser A and fiber laser B with the same 4.76-W SHG power and 0.07-nm SHG linewidth. The essential difference between the two fiber lasers is the power ripple of the SHG radiation, as is illustrated by Fig. 3a, b, which are obtained from the extraction of 0.1 % SHG power and are recorded by an AC-coupled 200-MHz bandwidth oscilloscope. One can find that the SHG from fiber laser B yields about 3.5 times more ripples of light intensity than those from fiber laser A. Figure 3c, d.are recorded by a "real-time" FFT-type spectrum analyzer [31], and they show that the main frequency distributions of the pumping noises lie below 15 kHz. For the noises in Fig. 3 whose frequencies are larger than 15 kHz, the noise level of fiber laser A (Fig. 3c) rapidly shrinks to almost zero. However, the noise level of fiber laser B still remains significant (Fig. 3d). The high-frequency (>15 kHz) ripple from fiber laser B can rapidly change the refraction index of the Ti:S crystal [23] and consequently arouses a random phase modulation upon laser pulse. Laser pulses would be chirped [32] by pump-power ripple. Thus, pump-power ripple would be a serious issue in terms of comb laser applications. We find that in our gigahertz dual-comb system, the quality of repetition rate and comb mode is very sensitive to the high-frequency (>15 kHz) pump-power ripples, especially when the pump power is tightly focused into the Ti:S crystal. Figure 4 displays the frequency qualities of Ti:S laser from two different pump-power ripples. The signal-to-noise ratio of repetition rate is roughly 80 dB when pumped by fiber laser A (Fig. 4a), while it is 50 dB when pumped by fiber laser B (Fig. 4b).This is because the optical path length of the Ti:S laser cavity is changed by the pump-power ripple. Similarly, the chirping of pulse will change the group delay dispersion (GDD) [32], leading to the broadening of the offset frequency and comb mode frequency. The broadening of the comb mode frequency is shown in Fig. 4c, d, where the laser mode is inspected by measuring the beatnote between one mode of comb laser and a free-run ECDL laser (100-kHz laser linewidth). Note that, for those applications of comb laser that the spectral resolution larger than 10 MHz [5, 25, 26], both pumping sources (fiber laser A and fiber laser B) actually work well in terms of starting a stable mode-locking with their laser frequency stabilized.

Figure 5 shows the comparison between two pulses in a time-domain that are pumped by two different fiber lasers and recorded by an interferometric autocorrelator. The black solid trace represents the pulse that is pumped by fiber laser A; the red-dashed trace is recorded when fiber laser A is replaced by fiber laser B. The change of the carrier-envelop phase $\Delta\phi_{\text{n}}$ at the nth fringe in Fig. 5 is characterized by measuring the time deviation ($\Delta\tau_n = \tau_n - \tau_{n-1}$) between two successive fringe width (τ_n), divided by a standard time interval (τ_0) of one assigned fringe and times 2π, that is,

$$\varphi(t) = \sum_0^n \Delta\varphi_n = \sum_0^n 2\pi\Delta\tau_n(t)/\tau_0,$$

where $\phi(t)$ stands for the carrier-envelop phase at time t. Here, the fringe at the pulse center, where zero of phase is defined, is assigned to be the aforementioned standard fringe with τ_0 time interval. In other words, the $\phi(t)$ in the upper right of Fig. 5 is the phase relative to that of pulse center ($t = 0$). From Fig. 5, one can find that the pulse is significantly chirped when Ti:S laser is pumped by fiber laser B, of which the change of phase is quadratically fitted. This implies that a nonlinear time-domain phase modulation happens to the pulse pumped by fiber laser B, a finding that confirms the interpretation of the degrading on the comb mode (Fig. 4d) in frequency-domain.

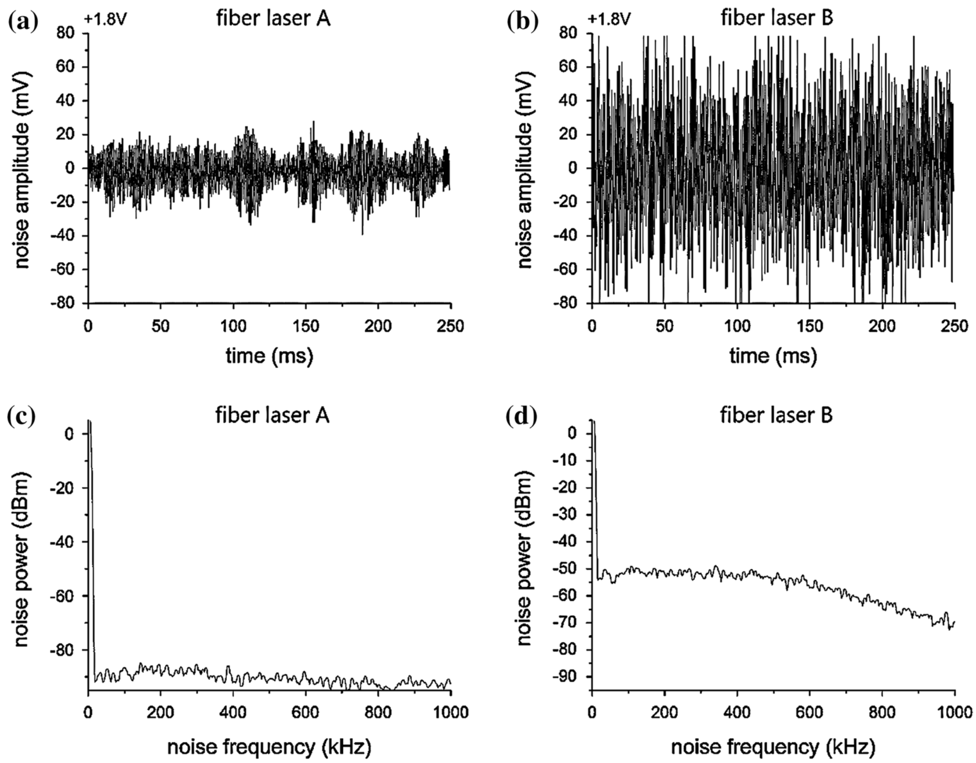


Fig. 3 **a**, **b** The time-domain power fluctuation of two pump lasers, recorded from the 10^{-4} light intensity of their SHG power (4.76 W) and with a 100-MHz bandwidth detector and AC-coupled oscilloscope. **c**, **d** the corresponding noise spectrum of (**a**, **b**), respectively, showing that fiber laser A yields 40-dB better noise ground comparing to that of fiber laser B in the case of high-frequency region (>15 kHz)

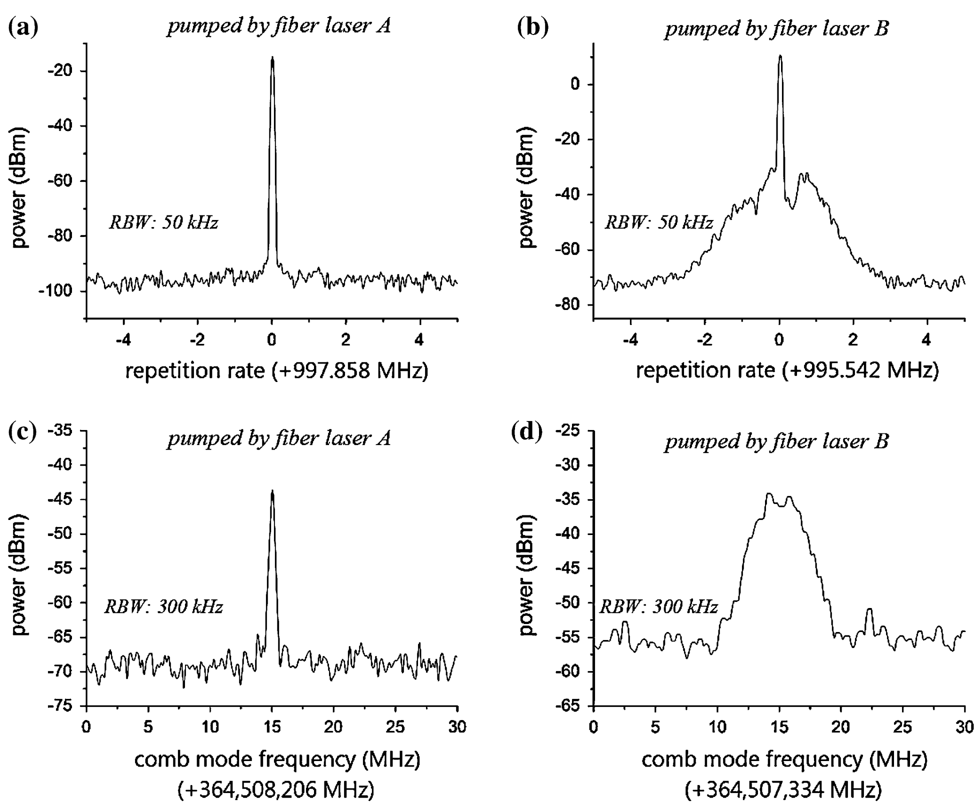


Fig. 4 Linewidths of repetition rate **a**, **b** and one laser mode **c**, **d** of our mode-locked lasers pumped by two different fiber lasers for comparison, where the two mode-locked lasers are in freely running; RBW: resolution band width. The transverse axis in Fig. 4c, d, titled "comb mode frequency", stands for the absolute frequency of one comb mode whose frequency is closest to the frequency of cesium atom 6S-8S F = 4→F = 4 hyperfine transition, see text

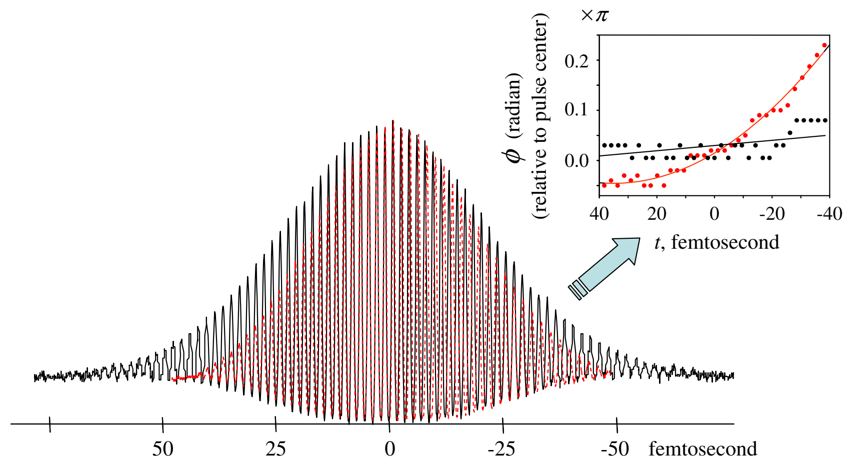


Fig. 5 Interferometric autocorrelation traces obtained from the output of comb #1 in Fig. 1. Two different pumping sources are alternated for comparison. The *black solid line* is the pulse pumped by fiber laser A and the *red-dashed line* is the pulse pumped by fiber laser B. *Upper right* The pulse phase (ϕ) versus time, in which the pulse phase at pulse center is defined as zero, see text

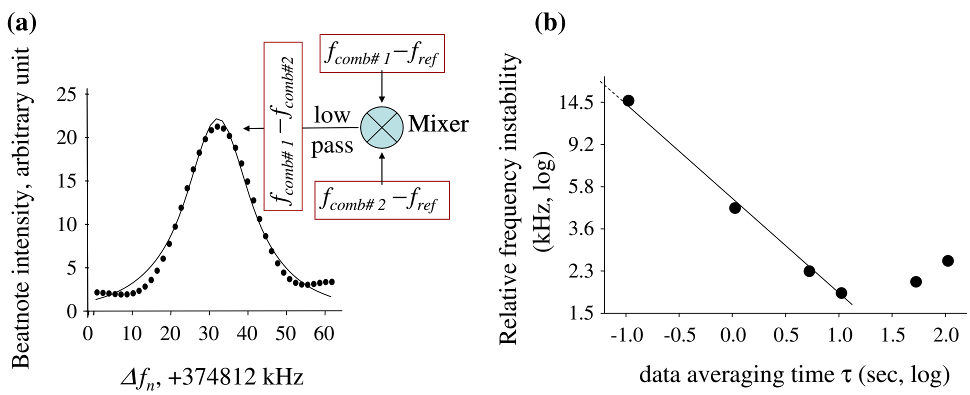


Fig. 6 **a** The nth comb pair Δf_n from the beat of our two comb laser lasers where a 20-kHz linewidth (FWHM) is derived by a Lorentian fitting (*black solid curve*). Note that the frequency modulation from reference laser (f_{ref}) does not appear to the lineshape. The attached block diagram illustrates how the beatnote is extracted (all the symbols are the same as that used in Fig. 1); **b** Frequency instability of one comb mode relative to reference laser

2.2 Comb pair coherence and comb frequency accuracy

The beatnotes of two comb lasers would comprise of the fundamental beatnote (Δf) and an offset (α) with its harmonics ($\alpha + n\Delta f \equiv \Delta f_n$). The phrase of "$n$th comb pair" in this report means the two modes that form the aforementioned nth beatnote (Δf_n). The linewidth and frequency accuracy of each comb pair (CP) are vital for all kinds of dual-comb-based spectrometers. For example, smaller Δf_r (difference of repetition rate) would be better for resolving wider range of spectra, but Δf_r should be larger than the linewidth as well as the frequency jitter of each CP for not losing any spectrum of interest. In other words, narrower CP linewidth and more stable CP frequency would help for resolving wider range of dual comb-based spectra. Furthermore, data acquisition should be accomplished within the coherence time between two comb lasers, where the coherence time is inversely proportional to the linewidth of each CP. The reference laser is useful for inspecting the CP linewidth since the amplitude of the beatnote between reference laser, and one comb mode would be much larger than each direct beatnote between two comb lasers. Figure 6a shows the CP linewidth of the Δf_n from which a 20-kHz linewidth (Lorentian fit) is derived. Therefore, the coherence time between two comb lasers is estimated as around 50 μs. Note that the frequency modulation of reference laser does not affect the two comb coherence measurement, as shown in Fig. 6a.

The frequency accuracy of each comb mode in our dual-comb system would be affected by the following two facts: one is the beat frequency instability when one comb mode is offset-locked to the reference laser and the other is the frequency accuracy of reference laser. When a comb mode is frequency-locked against the reference laser, the instability of their beat frequency is displayed on Fig. 6b; two comb lasers have similar frequency-locking instability. That is, our comb mode could follow the frequency of reference laser with 2-kHz locking instability at 10 s data averaging time. When the frequency of the reference laser is locked against the aforementioned cesium two-photon transition where a 150-Hz frequency instability at 10 s data averaging time has been demonstrated [12, 13], the accuracy of the comb mode frequency is then estimated as 10-kHz according to the result of the absolute frequency measurement in reference [13].

3 Summary and Perspective

In this paper, we design a dual Ti:S mode-locked laser system using a fiber laser-based pumping source. We upgrade the dual-ultrashort laser system to a dual-comb system by implementing a hand-sized reference laser. Common noise rejection of two repetition rates is achieved by sharing the same cooling base. We compare two different pumping sources to show the influences of pump-power ripples on comb lasers. The two combs coherence time is 50 μs from the CP linewidth measurement; the frequency accuracy of each comb mode is estimated as 10-kHz [13]. Table 1 lists the specifications of our dual-comb system, where some parameters are chosen according to the demands of our future works on spectroscopy. That is, 1-GHz repetition rate, 100-kHz Δf_r and 2.4-THz optical filter are chosen. To insure that the maximum RF spectra of dual-comb spectroscopy is a one-to-one mapping to the corresponding optical transition, $n\Delta f_r$ at any positive integer n is required not to exceed half of the repetition rate; that is, $n\Delta f_r \leq 0.5 f_{\rm rep}$ is required. Therefore, in Table 1, $n_{\max}$ is defined as the maximum value of n that satisfies the inequality of $n\Delta f_r \leq 0.5 f_{\rm rep}$ and the corresponding "maximum free spectral range" (MFSR) is defined as $n_{\max} \times \Delta f_r$, which stands for the widest range of dual-comb-based spectra in that each spectrum could be uniquely identified. The actual bandwidth $\Delta \nu_{bw}$ in Table 1 is determined by the employed optical filter [4] and is set to be 2.4 THz here. Therefore, the corresponding data acquisition time "T" in Table 1 is 10 μs [4]. Note that "T" does not mean the time for resolving the entire spectra with the range of $\Delta \nu_{bw}$ unless the entire comb modes of two lasers could be synchronously swept to the frequency range of half a repetition rate. Our dual-comb system have been examined to be able to sweep the two repetition rates synchronously with a fixed Δf_r to result in a 500-MHz mode frequency tuning range at 800 nm, with the sweep time smaller than 1 ms.

Since the easy-reinstall fiber laser pumping scheme and the hand-sized reference laser has improved the convenience of the whole dual-comb laser system and has saved the needed space for two sets of self-reference optics, the ongoing work of moving the entire system to a chemistry laboratory becomes much easier. We are implementing the dual-comb system into a molecular-beam-based apparatus to resolve the spectra of YC_2 radical molecule at the wavelength near 800 nm, in which the spectral width reported previously was no better than 42 MHz [33–35]. The linear extrapolation of Fig. 6b to 10 μs data averaging time is around 350 kHz and two comb lasers have similar instability. In other words, the relative frequency instability between two comb lasers would be <1 MHz. Therefore, by our dual-comb laser system with the aforementioned 1 ms frequency sweep time, it is possible to monitor the variation in YC_2 spectra that are subjected to a slow change of environment.

Table 1 Specifications of our dual-comb system, for repetition rate $f_{\rm rep}$: 1 GHz, the difference of repetition $\Delta f_{\rm r}$: 100 kHz

Symbol	Physical meaning	Formula	In our system
$n_{\max}$	Maximum mode number within free spectral range	$0.5 \times f_{\rm rep}/\Delta f_r$	5×10^3
MFSR	Maximum free spectral range	$n_{\max} \times f_{\rm rep}$	5 THz
$\Delta \nu_{bw}$ [4]	Maximum resolved bandwidth ($\Delta \nu_{bw}$ should be smaller than MFSR)	set	2.5 THz
T	Data acquisition time at $\Delta \nu_{bw}$ (should be smaller than comb pair coherence time)	$4\ \Delta \nu_{bw}/f^2_{\rm rep}$	10 μs
ni	The mode numbers involving in the $\Delta \nu_{bw}$	$\Delta \nu_{bw}/f_{\rm rep}$	10^3

Acknowledgments The authors wish to extend their appreciation to the National Science Council (NSC) of R.O.C. under contract no. NSC 102-2112-M-008-010 for supporting this project and the financial support from Chunghua Telecom Laboratories. We are grateful to NSC AMO focus group of Taiwan and CQSE of National Taiwan University who offered nice platforms for useful research communications.

References

1. S.-J. Lee, B. Widiyatmoko, M. Kourogi, M. Ohtsu, Ultrahigh scanning speed optical coherence Tomography using optical frequency comb generators. JJAP **40**, 878 (2001)
2. F. Keilmann, C. Gohle, R. Holzwarth, Time-domain mid-infrared frequency-comb spectrometer. Opt. Lett. **29**, 1542 (2004)
3. I. Coddington, W.C. Swann, N.R. Newbury, Coherent multiheterodyne spectroscopy using stabilized optical frequency combs. Phys. Rev. Lett. **100**, 013902 (2008)
4. N.R. Newbury, I. Coddington, W.C. Swann, Sensitivity of coherent dual-comb spectroscopy. Opt. Express **18**, 7929 (2010), and the references therein
5. T. Ideguchi, B. Bernhardt, G. Guelachvili, T.W. Hänsch, N. Picqué, Raman-induced Kerr-effect dual-comb spectroscopy. Opt. Lett. **37**, 4498 (2012)
6. R.J. Jones, K.D. Moll, M.J. Thorpe, J. Ye, Phase-coherent frequency combs in the vacuum ultraviolet via high-harmonic generation. Phys. Rev. Lett. **94**, 193201 (2005)
7. A. Ozawa, J. Rauschenberger, Ch. Gohle, M. Herrmann, D.R. Walker, V. Pervak, A. Fernandez, R. Graf, A. Apolonski, R.

Holzwarth, F. Krausz, T.W. Hänsch, T. Udem, High harmonic frequency combs for high resolution spectroscopy. Phys. Rev. Lett. **100**, 253901 (2008)

8. For example, in the field of astronomy (so-called astro-comb) that needs the Ti:S comb laser to be implemented in a remote observatory. C. H. Li, A. J. Benedick, P. Fendel, A. G. Glenday, F. X. Kärtner, D. F. Phillips, D. Sasselov, A. Szentgyorgyi, and R. L. Walsworth, A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}. Nature **452**, 610 (2008)
9. T. Ideguchi, S. Holzner, B. Bernhardt, G. Guelachvili, N. Picqué, T.W. Hänsch, Coherent Raman spectro-imaging with laser frequency combs. Nature **502**, 355 (2013)
10. D.J. Jones, S.A. Diddams, J.K. Ranka, A. Stentz, R.S. Windeler, J.L. Hall, S.T. Cundiff, Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis. Science **288**, 635 (2000)
11. G.K. Samanta, S. Chaitanya Kumar, M. Ebrahim-Zadeh, Stable, 9.6 W, continuous-wave, single-frequency, fiber-based green source at 532 nm. Opt. Lett. **34**, 1561 (2009)
12. Y.-H. Chen, T.-W. Liu, C.-M. Wu, C–.C. Lee, C.-K. Lee, W.-Y. Cheng, High-resolution 133Cs 6S-6D, 6S-8S two-photon spectroscopy using an intracavity scheme. Opt. Lett. **36**, 76 (2011)
13. C.-M. Wu, T.-W. Liu, M.-H. Wu, R.-K. Lee, W.-Y. Cheng, The absolute frequency of cesium 6S-8S 822-nm two-photon transition by a high-resolution scheme. Opt. Lett. **38**, 3186 (2013)
14. J. Ye, S. Cundiff, *Femtosecond optical frequency comb technology* (Springer, Boston, 2005)
15. D. Aumiler, T. Ban, N. Vujicic, S. Vdovic, H. Skenderovic, G. Pichler, Characterization of an optical frequency comb using modified direct frequency comb spectroscopy. Appl. Phys. B **97**, 553 (2009)
16. T. Rosenband, D.B. Hume, P.O. Schmidt, C.W. Chou, A. Brusch, L. Lorini, W.H. Oskay, R.E. Drullinger, T.M. Fortier, J.E. Stalnaker, S.A. Diddams, W.C. Swann, N.R. Newbury, W.M. Itano, D.J. Wineland, J.C. Bergquist, Frequency ratio of Al^+ and Hg^+ single-ion optical clocks; metrology at the 17th decimal place. Science **319**, 1808 (2008)
17. J. Ye, L.-S. Ma, J.L. Hall, Molecular iodine clock. Phys. Rev. Lett. **87**, 270801 (2001)
18. A. Benedick, D. Tyurikov, M. Gubin, R. Shewmon, I. Chuang, Compact, Ti:sapphire-based, methane-stabilized optical molecular frequency comb and clock. Opt. Lett. **34**, 2168 (2009)
19. T.C. Schratwieser, K. Balskus, R.A. McCracken, C. Farrell, C.G. Leburn, Z. Zhang, T.P. Lamour, T.I. Ferreiro, A. Marandi, A.S. Arnold, D.T. Reid, ^{87}Rb-stabilized 375-MHz Yb:fiber femtosecond frequency comb. Opt. Express **22**, 10494 (2014)
20. T. Udem, J. Reichert, R. Holzwarth, T.W. Hänsch, Absolute optical frequency measurement of the cesium D_1 line with a mode-locked laser. Phys. Rev. Lett. **82**, 3568 (1999)
21. IPG Photonics Inc., YLR-30-1064-LP-SF
22. The SHG crystal used in this paper was bought from HC PHOTONICS CORP
23. J. Stenger, H.R. Telle, Intensity-induced mode shift in a femtosecond laser by a change in the nonlinear index of refraction. Opt. Lett. **25**, 1553 (2000)
24. GIGAOPTICS, GIGAJET TWIN 20c/20c
25. T. Ideguchi, A. Poisson, G. Guelachvili, T.W. Hänsch, N. Picqué, Adaptive dual-comb spectroscopy in the green region. Opt. Lett. **37**, 4847 (2012)
26. T. Ideguchi, A. Poisson, G. Guelachvili, N. Picqué, T.W. Hänsch, Adaptive real-time dual-comb spectroscopy. Nature Commun. **5**, 3375 (2014)
27. Agilent Inc., 8643A and 8644B
28. Fluke Inc., 6080A
29. The laser was kindly lent by MPB Inc. with a customized design from model YFL-P-20-1120 that allowed customer for controlling the current of pumping laser (diode laser)
30. Coherence Inc., Verdi-6
31. Tektronix Inc., RSA3408A
32. J. -C Diels, W. Rudolph, *Ultrashort laser pulse phenomena* (Academic Press, San Diego, 1996)
33. T.C. Steimle, A.J. Marr, J. Xin, A.J. Merer, K. Athanassenas, D. Gillett, Optical detection of yttrium dicarbide, a "T-shaped" molecule. J. Chem. Phys. **106**, 2060 (1997)
34. R.R. Bousquet, T.C. Steimle, permanent electric dipole moment of yttrium dicarbide, YC_2. J. Chem. Phys. **114**, 1306 (2000)
35. T.C. Steimle, R.R. Bousquet, K.C. Namiki, A.J. Merer, Rotational analysis of the $\tilde{A}^2A_1$–$X \sim {}^2A_1$ band system of yttrium dicarbide: YC_2. J. Mol. Spectrosc. **215**, 10 (2002)