Quantum Cryptography with Injection-Locked Dual-Wavelength Diode Laser

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Abstract: Master-to-slave injection-locked dual-mode diode laser is proposed for providing the single-photon DPS-QKD transmission at a shifted key rate of 1 Gbit/s with >3000-sec decoding stability under an interferometric visibility of 99.2% and dual-wavelength usage security. © 2024 The Author(s)

1. Introduction

Master-to-slave (M-to-S) injection-locked diode laser is one of the well-known and cost-effective coherent sources for implementing the optical quantum key distribution (QKD) with differential phase-shift-keying (DPS) protocol [1]. With using the single-mode narrow-linewidth diode laser under a direct modulation with the DPS protocol as a master, any kind of diode laser with the feasibility of injection-locking controllable pulsation at wavelength and phase following the master source can be selected as the slave source. Unlike other optical DPS-QKD schemes realized using external modulation, when performing the M-to-S injection-locking for transferring the encrypted DPS code stream from the directly intensity modulated master diode laser to the phase of a slave diode laser pulsated with the QKD bit, the wavelength matching master and slave diode lasers is the only solution for such a M-to-S injection-locked DPS-QKD encoder owing to the inherent limitation on the wavelength tunable range set for injection-locking [2]. Among the potential candidates for serving as the slave laser, the energy consumption gradually becomes a considerable issue as the diode lasers with higher resonant cavities and larger output power often demand a large external injection power for performing the wavelength injection locking. To save the energy exhausted on the high end-facet reflectance and to explore the wavelength-division-multiplexing (WDM) channelization capability of the salve diode laser, a new-class of the diode laser with dual-wavelength lasing at lower end-facet reflectance, broader modal spectrum, and wider injection-lockable wavelength range is proposed for serving as the wavelength switchable and lockable DPS-QKD carrier with easier WDM channel selectivity. This feature can further be adapted to perform a more secure DPS-QKD as both phase and wavelength become unpredictable with only one mode injection-locked and only single-photon transmitted after attenuating such a dual-wavelength QKD carrier. Such a superiority preserves the data authentication with increasing the complexity via concurrent wavelength selection and phase coding under the on/off injection-locking. In this work, the DPS-QKD encryption through the M-to-S injection-locking and binary phase shift keying of the dual-wavelength diode laser at one selected mode is demonstrated, which effectively adds another dimension of encryption in addition to the polarization BB84 or phase DPS coding for securely delivering the quantum key. The wavelength switchable single-photon DPS-QKD is performed to realize the advanced single-photon DPS-QKD with a dual-mode diode laser under M-to-S injection-locking.

2. Experimental setup

Figure 1(a) shows the butterfly mount package of the coherent master source served by a single-mode distributed feedback laser diode (DFBLD), and Figure 1(b) shows the slave source served by the dual-mode diode laser packed within a single-mode-fiber (SMF) pigtailed TO-can. The master and the salve are temperature-sensed via thermistors, feedback controlled via a thermo-electric-cooler, and heat dissipated through the bottom mount.

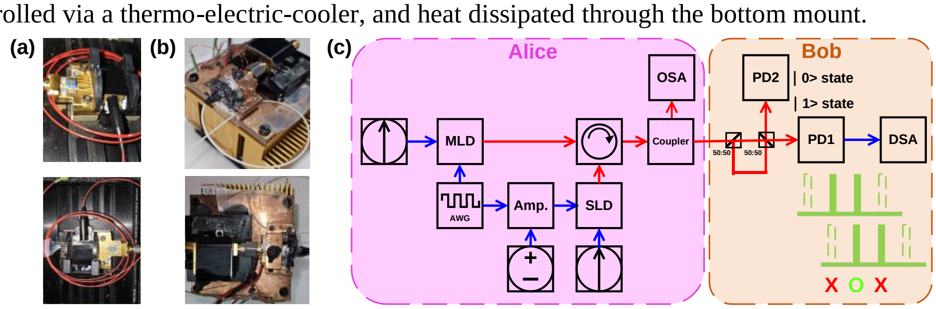

Fig. 1 The packages of (a) the signal-mode master DFBLD with butterfly mount and (b) the dual-mode slave DFBLD with cooper mount; (c) the experimental setup of a DPS-QKD coded transmission system with M-to-S injection-locked transmitter paired single-photon detector.

Figure 1(c) illustrates the complete block diagrams of the optical transmitter (Tx) and the receiver (Rx) for M-to-S injection-locked DPS-QKD communication. Both the M-to-S injection-locking from master to slave port and the DPS-QKD transmission from Tx to Rx are performed through an optical circulator (OC). The DPS and QKD codes are synthesized with an arbitrary waveform generator with an identical data rate of 1 Gbit/s. Both the encoding and encoding parts are triggered with the distributed clock at the frequency of 10 MHz.

3. Result and discussion

As the QBER in direct proportion with the visibility can also be inferred to correlate with the reciprocal linewidth of the QKD carrier according to Honjo's work [3], a lower spectral linewidth obtained with a higher bias of the master as well as the stronger M-to-S injection-locking of the slave is demanded to reduce the QBER. However, both the electrical and thermal noises would transfer to broaden the linewidth. By employing different current and temperature controllers, the self-heterodyned linewidth measured as a function of bias current is presented to show a good correlation with the power-dependent Lorentzian linewidth of $\delta\nu=\pi h\nu(\Delta\nu^2)/P_{out}$ predicted by Schawlow *et al.* [4], in which $\Delta\nu$ denotes the master bandwidth (half width at half maximum, HWHM), P_{out} the master output power linearly proportional to the current of (I-Ith), $\delta\nu$ the master lasing linewidth. Under the same temperature control, the lower noise from current sources reveals a significant influence on the e-h pair density and the spontaneous emission for providing the narrower linewidth down to 70.5 kHz at a DC bias up to 7 Ith, as shown in Fig. 2(a). With selecting the low-noise current source and comparing two temperature controllers, the lower part of the Fig. 2(a) indicates that the thermal noise also plays an important role in further reducing the lasing linewidth by more than 13% to 63 kHz when biasing at 7 Ith. In Fig. 2(b), the self-heterodyned lasing mode spectrum and the numerically fitted linewidth at -20dB decaying point (divided by a factor of 1/2√99) are shown for comparing two different master DFBLDs. The LDs are selected for subsequent experiments as they offer sufficiently narrow linewidth of 63-68 kHz after biasing beyond 4 times its threshold.

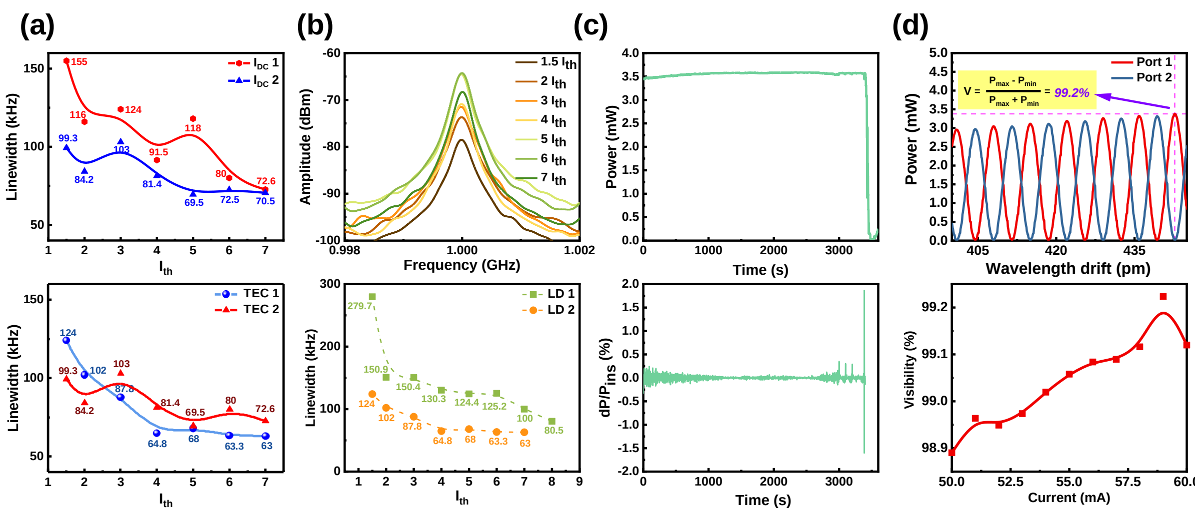

Fig. 2 (a) The bias dependent linewidth of the master DFBLD measured with different current sources under same controller (upper) and different temperature controllers under same current source (lower); (b) the bias dependent self-heterodyned lasing modal spectra of the master laser (upper) and the numerically fitted linewidths for two master master DFBLDs for selection; (c) the interfered power stability (upper) and the logarithemic differential power diagram of the master after passing through the DLI for characterizing the wavelength fluctuation, and (d) the wavelength dependent output powers recorded for two ($\cos^2\phi$ and $\sin^2\phi$) ports (upper) and the current-dependent interferometric visibility (lower) for the master output after passing through the passively adiabatic controlled DLI.

To perfectly 1-bit-delay decode the transmitted DPS-QKD bits with a longer code sequence in the DLI, the best result is essentially relying on setting the M-to-S injection-locked QKD carrier at the wavelength correlated with the maximal visibility of the DLI and suppressing any noises occurred to disturb both the master lasing and M-to-S injection-locking wavelengths. The upper part of Fig. 2(c) reveals a extremely stable constructive output of the DLI with passing through the continuous-wave master DFBLD for almost over 3600 seconds is ensured for performing the long-term decoding with its deviation power fluctuation as small as ±0.2% (the smallest value can approach ±0.05% for at least 1500 seconds), as shown in the lower part of Fig. 2(c). Such superior stability is mainly attributed to the passive adiabatic isolation by insulating all of the DLI components from external environmental temperature fluctuations and mechanical vibrations. In addition to maintaining the long-term output stability at the maximum/minimum of the DLI, the maximization of the interferometric visibility between output channels is mandatory for the QBER reduction. As shown in the upper part of Fig. 2(d), the visibility gradually approaches its maximum of 99.2% with continuously red-shifting the master wavelength to measure the periodically varied output powers for the dual-channel DLI, which infers the achievable QBER of 0.4% according to the formula QBER = (1 - V)/2. By scanning the bias current of the master DFBLD from 50%-60% passing through the DLI, the measured visibility can also enlarge from 98.9% to 99.2%, as shown in the lower part of Fig. 2(d). Moreover, the experimental results also declare that even with a change in the applied bias current of ±5 mA for the master DFBLD, the interferometric visibility of DLI can remain within ±0.15% fluctuation, hovering around 99%, as shown in Fig. 2(d).

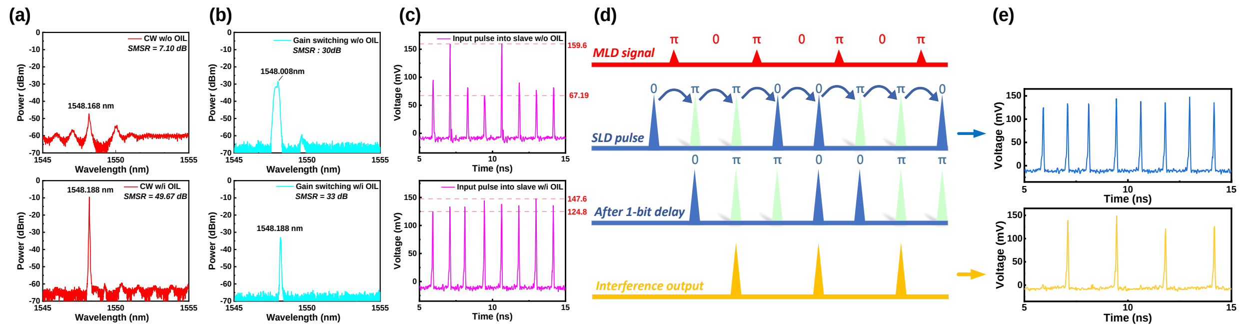

Fig. 3 The spectra of the dual-mode slave biased at (a) I_{DC}=0.5Ith w/o injection-locking (upper) and w/i injection (lower), (b) in continuous-wave optical spectra and (b) gain switched spectra; (c) time domain waveform processing gain switched pulse ; (d) Schematic diagram of signal (phase/intensity) modulation; (e) time domain waveform in slave pulse and output signal after DI interference, respectively.

For M-to-S injection-locking, the dual-mode slave is expected not to lase at the free-running condition to facilitate the injection-locking efficiency, and the electrical pulsed QKD bit repeated at 1-GHz period is combined with the below-threshold DC current to drive the slave. The upper part of Fig. 3(a) illustrates the optical spectrum of the 0.5Ith-biased dual-mode slave nearly continuous-wave lasing at the free-running case, which can be M-to-S injection-locked lasing at the master's wavelength to provide an enhanced side-mode suppressing ratio (SMSR) of approximately 42 dB, as can be seen in the lower part of Fig. 3(a). The effective injection-locking suppresses other side modes to facilitate the photons with concentrated energy and narrow linewidth for improving the interferometric visibility during DPS-QKD decoding. With pulsating the dual-mode slave diode laser biased at below threshold, the slave wavelength slightly blue-shifted by 0.16 nm and is still single-mode pulsed lasing at the master wavelength after M-to-S injection-locking, as shown in Fig. 3(b). When comparing the optical spectra of the gain-switched pulsating slave with and without master injection-locking in Fig. 3(b), the chirped and overshot phenomena of the gain-switched spectrum are observed to cause a significant amplitude fluctuation of 54.4% before injection-locking, whereas the gain-switched pulsating spectrum narrows down to provide a less fluctuated (decreased to 14.2%) pulse-train for a better DPS-QKD transmission performance after M-to-S injection-locking, as shown in Fig. 3(c). The M-to-S injection locking also stabilizes the timing sequence of the QKD pulsed carrier with reduced jitter for improving the receiving QBER. Finally, the binary DPS and pulsed QKD code sequences depicted in Fig. 3(d) are employed to respectively encode the master and slave sources. The master DPS code was successfully transferred to the slave QKD bit by executing the M-to-S injection-locking, and the 1-bit-delay decoded slave DPS-QKD output from the DLI is recorded for time-stamping and code certification between transmitting and receiving users. The finalized QBER is determined as <4%, which is qualified for passing through the criterion of error correction.

4. Conclusion

The master-to-slave injection-locked dual-mode diode laser is proposed for providing the single-photon DPS-QKD transmission at a shifted key rate of 1 Gbit/s with >3000-sec decoding stability under an interferometric visibility of 99.2% and dual-wavelength usage security. The effects of chirping and overshooting that occurred on the gain-switched pulsation of the dual-mode slave can be suppressed by optimizing the DC biasing point and RF pulsating amplitude to equalize the pulsed QKD bit amplitude through the wavelength-matched M-to-S injection-locking, thus minimizing timing jitter for the QKD bit and phase error for the DPS code transferred from the direct-modulated master to the injection-locked slave for reaching the error-free QBER of <4%.

5. Reference

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