Distributed ultrafast fibre laser

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A traditional ultrafast fibre laser has a constant cavity length that is independent of the pulse wavelength. The investigation of distributed ultrafast (DUF) lasers is conceptually and technically challenging and of great interest because the laser cavity length and fundamental cavity frequency are changeable based on the wavelength. Here, we propose and demonstrate a DUF fibre laser based on a linearly chirped fibre Bragg grating, where the total cavity length is linearly changeable as a function of the pulse wavelength. The spectral sidebands in DUF lasers are enhanced greatly, including the continuous-wave (CW) and pulse components. We observe that all sidebands of the pulse experience the same round-trip time although they have different round-trip distances and refractive indices. The pulse-shaping mechanism of the DUF laser is dominated by the dissipative processes in addition to the phase modulations, which makes our ultrafast laser simple and stable. This laser provides a simple, stable, low-cost, ultrafast-pulsed source with controllable and changeable cavity frequency.

Ultrafast fibre lasers, which play an important role in modern research and industrial applications, have attracted considerable attention because of their compactness, reliability, low cost, and easy turnkey operation1–3. Passive mode-locking is an efficient way of generating picosecond and femtosecond pulses4–7. Passively mode-locked (PML) fibre lasers have evolved from fundamental science to commercial instruments, with widespread applications in optical communications, medicine, and materials processing8–12. The saturable absorber is a key element for the PML fibre lasers. Currently, various saturable absorbers have been proposed, such as the nonlinear polarisation rotation13,14, nonlinear optical loop mirror15,16, semiconductor saturable absorber mirror17,18, graphene19,20, and single-walled carbon nanotube (SWNT)21,22. Among them, SWNTs are particularly interesting for ultrafast lasers because they have high environmental stability and are independent of the polarisation of pulses evolving in the laser cavity23–25.

The most common type of laser cavity is the Fabry–Perot cavity, which is made by placing the gain medium between two high-reflecting mirrors26–28. The general solution is to deposit dielectric mirrors directly onto the polished ends of a fibre. Another solution is to use fibre Bragg gratings (FBGs) for the mirrors23; this has been widely employed in past decades because of its simple design. Recently, linearly chirped fibre Bragg gratings (LCFBGs) have been observed to provide an excessive amount of negative dispersion inside the laser cavity; e.g., a 10-cm-long grating can compensate the dispersion acquired over fibre lengths of 50 km29. When the PML fibre laser operates at the fundamental cavity frequency, it delivers a pulse train whose individual pulses are spaced by the round-trip time inside the laser cavity. When the mirror of the laser cavity is distributed (e.g., LCFBG) rather than concentrated (e.g., dielectric mirror), the round-trip distance for different frequencies of pulse is different. Although the distributed lasers can deliver the continuous-wave (CW) lasing28–31, they challenge the mode-locking operation because the frequency spacing among the modes should be constant rather than varied32,33.

The PML fibre laser with chirped FBG design was first reported in 199534,35. This type of linear-cavity laser is widely utilised in modern research and industrial applications because of the all-fibre structure, easy fabrication, and reliability. In general, the LCFBG is employed as a wavelength selection or dispersion management component34–40 so that such lasers typically emit pulses at an individual wavelength with a fixed repetition rate. It is worth noting that the characteristics of the distributed reflection were ignored in previous reports. Thus far, no distributed ultrafast (DUF) phenomenon in fibre lasers has been reported. The pulse-shaping mechanism for DUF fibre lasers is absent because the nonlinear effects in this type of laser are difficult to balance the very large anomalous dispersion induced by the LCFBG.

In this paper, a DUF fibre laser using an LCFBG is proposed and demonstrated experimentally. It differs from the conventionally concentrated ultrafast fibre lasers because the total cavity length of the DUF laser is linearly changeable as a function of the pulse wavelength, Broadband wavelength tuning (from ~1556 to ~1564 nm) is reported, corresponding to ~2 kHz of the tunable range of the fundamental cavity frequency. The spectral sidebands, which are composed of CW and pulse components and are distinct from the Kelly sidebands in the
conventional soliton fibre lasers\(^{31,43}\), are greatly enhanced. We observe that the pulse-shaping of the DUF laser is dominated by the dissipative processes in addition to the phase modulations, which is completely different from the common net-anomalous-dispersion or net-normal-dispersion lasers. Our unique experimental observations are also confirmed by our numerical simulations.

**Results**

**Laser set-up and operation.** The key component of a DUF laser, shown in Figs. 1(a)–1(c), is an LCFBG that introduces a distributed operation for ultrafast pulse generation in this laser. Note that it also provides a large amount of dispersion, up to \(-5.2 \text{ ps}^2/\text{cm}\) (over 10 times larger than the standard fibre), by the concept of the photonic band gap. The experimental set-up is shown in Fig. 1(a) (see Methods for details). The LCFBG is spliced in a standard linear laser cavity. A polarisation controller is employed to control the central wavelength of laser operation by means of the polarisation-dependent loss.

The operational principle of the laser is illustrated in Fig. 1(b). The different parts of the LCFBG reflect the different wavelengths \(\lambda\). The left and right mirrors operate to concentrate and distribute, respectively. The proposed laser cavity is clearly very different from the conventional Fabry–Perot cavity that can provide laser operation with well-defined, equally spaced longitudinal modes. The total length of the laser cavity here is changeable rather than constant with respect to the central wavelength \(\lambda\), which is completely different from the common net-anomalous-dispersion or net-normal-dispersion lasers. Our unique experimental observations are also confirmed by our numerical simulations.

**Distributed-operation cavity effect.** Self-starting mode-locking operation starts at the pump power of \(P \approx 10\text{ mW}\). By appropriately adjusting the settings of the polarisation controller, the proposed laser delivers the pulses with the different central wavelengths and repetition rates. The typical output spectra at \(P = 13\text{ mW}\) are shown in Fig. 2(a), with the central wavelengths \(\lambda_{1-4}\) of 1556.36, 1558.25, 1561.45, and 1564.25 nm. The corresponding fundamental cavity frequencies are 5.733487, 5.733062, 5.732286, and 5.731641 MHz, respectively, as shown in Fig. 2(b). The cavity frequency is changed at different wavelengths because the total length of the cavity is automatically adjusted based on the operational wavelength by the LCFBG. This confirms our concept of distributed-operation design. The schematic diagram is demonstrated in Figs. 1(b) and 1(c). If the total length of cavity for \(\lambda_{1}\) is \(L\), it is approximately \(L + 2.6\), \(L + 7.1\), and \(L + 11\) mm for \(\lambda_{2-4}\), respectively. The radio frequency (RF) spectra in Fig. 2(b) give a signal-to-noise ratio of \(>60\text{ dB}\) (\(>10^6\) contrast), showing low-amplitude fluctuations and good mode-locking stability\(^{44}\).

Figures 3(a) and 3(b) show the relationships of the fundamental cavity frequency \(F\) and the relative difference of cavity length, \(\Delta L\), with respect to the central wavelength \(\lambda\), respectively. The square symbols denote the experimental data and the circle symbols are calculated from the experimental data. The difference of \(F\) and \(\Delta F\), is composed of two parts, i.e., \(\Delta F = \Delta F_{\text{Cavity}} + \Delta F_{\text{Fiber}}\). \(\Delta F_{\text{Cavity}}\) is from the relative difference of cavity length, \(\Delta L\), due to the distributed operation. \(\Delta F_{\text{Fiber}}\) originates from the group velocity dispersion of intra-cavity (i.e., EDF and SMF in the laser cavity). Here, the dispersions of EDF and SMF in the cavity can cause a frequency difference.

**Figure 1 | Set-up of DUF fibre laser.** (a) Cavity setup of the PML fibre laser incorporating a linearly chirped fibre Bragg grating (LCFBG). Inset: Reflection spectra of LCFBG. The LCFBG is spliced in a linear cavity containing a single-walled carbon nanotube (SWNT) saturable absorber (SA) to mode-lock ultrafast laser, a polarisation controller (PC) to act on the pulse polarisation and adjust the central wavelength, a gain fibre (EDF), a wavelength-division multiplexer (WDM) to couple the pump source (LD), and a high-reflecting dielectric mirror. A polarisation independent isolator (PI-ISO) forces the unidirectional output of the laser. The total length of linear cavity is \(\sim 17.7\text{ m}\) with \(-7\text{-m-long EDF and }\sim 15\text{-mm-long LCFBG.} (b) Schematic diagram of the LCFBG-based fibre laser. The LCFBG reflects the different wavelengths with respect to its position. Round-trip distance for a pulse with a shorter wavelength is less than that for a pulse with a longer wavelength. (c) The operation of ultrafast fibre laser with the central wavelength of \(\lambda_2\) and the spectral bandwidth of \(\Delta\lambda\). The blue area of the LCFBG reflects the spectra from \(\lambda_2 - \Delta\lambda/2\) to \(\lambda_2 + \Delta\lambda/2\). The different spectral components of the pulses propagate through the different distances in a round trip.
respectively. The central wavelengths of $\lambda_{1-4}$ are 1556.36, 1558.25, 1561.45, and 1564.25 nm, respectively.

We can observe from Fig. 3(a) that the fundamental cavity frequency $F$ decreases approximately linearly with the central wavelength $\lambda$. The solid lines in Fig. 3 are the fit lines with the expressions of $F = 6.09874 - 2.34677 \times 10^{-4} \cdot \lambda$ and $\Delta L = -2173.605 + 1.39657 \cdot \lambda$. It is seen from Fig. 3(b) that the difference of the total cavity length, $\Delta L$, approximately linearly increases along with $\lambda$, as interpreted from Fig. 1(b). Because of the linear chirp of the LCFBG, the grating period $\Lambda$ linearly increases along with the LCFBG (Fig. 1(b)). Then, the reflected wavelength of the grating also increases linearly along with the LCFBG because it is given by $\lambda = 2n\Lambda$. From Fig. 3(b), one can see that $\Delta L$ is $\sim 11$ mm when $\lambda$ increases from 1556.36 to $\sim 1564.25$ nm. The corresponding optical and RF spectra for $\lambda = 1556.36$ and 1564.25 nm are shown in Fig. 2.

**Laser characteristics and theoretical confirmation.** Figures 4(a)–4(d) show the optical spectra, autocorrelation traces, RF spectra, and oscilloscope traces respectively of lasers at $\lambda \approx 1560$ nm. The typical output spectra at the pump powers of $P \approx 10.6, 13.8,$ and 16.9 mW are shown in Fig. 4(a). The corresponding autocorrelation traces of the experimental data (circle symbols) and the sech$^2$–shaped fit curve are shown in Fig. 4(b). The full width at half maximum (FWHM) spectral width and the pulse durations ($\Delta t$) are approximately 0.64 nm and 4.7 ps, 0.70 nm and 4.3 ps, and 0.71 nm and 4.1 ps at $P \approx 10.6, 13.8,$ and 16.9 mW, respectively. Then, the corresponding time-bandwidth products are approximately 0.37, 0.37, and 0.36, respectively, which are slightly larger than the value of 0.315 for the transform-limited sech$^2$–shaped pulses. Figures 4(c) and 4(d) are the fundamental RF spectra with 1 Hz resolution and 100 Hz span and the wideband RF spectra up to 1 GHz, respectively. Figure 4(c) demonstrates that the repetition rate of the fundamental harmonic frequency is 5.732638 MHz, corresponding to 174.44 ns round-trip time (Fig. 4(c) inset). No spectrum modulation is observed above 1 GHz (Fig. 4(d)), indicating no Q-switching instabilities.

The experimental observations show that with the increase of the pump power $P$, the optical spectrum is hardly improved for the central wavelength whereas it is evidently enhanced for the sidebands. An example is shown in Fig. 4(a). At the same time, the pulse energy increases along with $P$, as shown in Fig. 4(b). We can see from Fig. 4(a) that when $P$ increases from 10.6 to 16.9 mW, the sideband is improved by $\sim 10$ dB (i.e., 10 times) although the spectral power at the central wavelength (i.e., 1560 nm) is hardly changed. The experimental results show that the maximum of the output average power of pulses is approximately 0.6 mW at $P \approx 22$ mW for the single pulse operation of the laser, corresponding to the pulse energy.
of $\sim 1$ nJ in the intracavity. When the pump power $P$ is beyond 22 mW, the laser operates on the dual-pulse regime.

To confirm the experimental observations, the typical results of numerical simulations of laser in the mode-locking regime are demonstrated in Fig. 5. In the modelling, in addition to the phase modulation, the dissipative processes (i.e., gain and loss processes) play a crucial role in driving the system to the steady-state solution. Note that the spectral filtering effect is ignored in the simulations. Parameters are chosen to match the experimental values (see Methods). It is seen from Fig. 5 that the spectral width and pulse duration are 0.695 nm and 4.99 ps, respectively. So the time-bandwidth product is approximately 0.43, showing that it is sech²-shaped pulses rather than Gaussian-shaped pulses. The pulse energy is approximately 0.5 nJ, which can be enhanced by increasing the
The numerical results (Figs. 5(a) and 5(b)) are in good agreement with the experimental observations, as shown in Fig. 4 (at the case of the pump power $P = 10.6$ mW). Figure 5(c) shows that the instantaneous frequency is low and nonlinear across the pulse. From the theoretical point of view, then, the pulses are hardly compressed and dechirped.

We can observe from Fig. 3(b) that the length of the working area of the LCFBG, $\Delta L$, is $\sim 1.39$ mm for 1 nm of wavelength difference. Then, the delay related to the LCFBG is $\sim 4.7$ ps when the FWHM spectral width of the pulse is 0.7 nm. This delay is approximately consistent with the pulse duration, as shown in the experimental and theoretical results (Figs. 4 and 5). Therefore, the spectral and temporal widths of pulses in the DUF lasers are dependent on the relative differences of cavity length.

**Strong enhancement of spectral sidebands.** Usually, no clear evidence of Kelly sidebands has emerged in stretched-pulse lasers, self-similar lasers, dissipative-soliton lasers, and graded-index multimode fibre lasers. By contrast, at the phase-matched frequencies of soliton lasers, the dispersive radiation builds up and causes Kelly sidebands on the spectrum. However, the Kelly sideband creation is a key limitation on the soliton energy of lasers. Then, the pulse energy of a conventional soliton is typically less than 0.1 nJ in the standard fibre. The theoretical predictions and experimental observations show that the pulse energy in this report can be up to 1 nJ.

The strongest peak of sidebands and the spectral power of the central wavelength are of the same order of magnitude for conventional soliton lasers. However, the experimental results here demonstrate that the power of the first-order sidebands is much stronger than that of the central wavelength, as shown in Figs. 2(a), 4(a), and 6(a). We can observe from Fig. 6(a) that the two strongest sidebands are over 17 dB (i.e., $\sim 50$ times) and 13 dB (i.e., $\sim 20$ times) larger than the spectral power of the central wavelength ($\sim 1563.4$ nm), respectively. The experimental observations show that, with the increase of pump power, the pulse energy and sidebands are enhanced but the power at the central wavelength is almost unchanged. By comparing the experimental observations (i.e., Fig. 4(a)) to the theoretical results (i.e., Fig. 5(a)), we can see that, for lower pump strength, the experimental results are in good agreement with the theoretical predictions. For higher pump strength, but, the power of the first-order sideband is much larger than that of the central wavelength, e.g., the former is 50 times larger than the latter (Fig. 6(a)). The modulation instability plays the key role for the higher pump strength.

The strongest two sidebands in Fig. 6(a) are separated from the pulse spectrum by a programmable optical filter. The solid curves in Figs. 6(c) and 6(e) are the separated sidebands with the spectral widths of 0.0079 and 0.011 nm, respectively. Figures 6(d) and 6(f) illustrate the autocorrelation traces of sidebands at 1562.1 and 1564.7 nm, indicating that the FWHM widths are $\sim 504$ and $\sim 364$ ps, respectively. They are much larger than the pulse duration of the laser (Fig. 6(b)).

**Discussion**

Fibre dispersion of the laser cavity plays a critical role in the evolution of pulses because different spectral components associated with the pulse travel at different speeds. Usually, the net-anomalous-dispersion fibre lasers support solitons through a balance between the dispersive and nonlinear effects. In the large normal dispersion lasers that have no intra-cavity dispersion control, the spectral filtering produces strong self-amplitude modulation that can dominate the pulse-shaping, which is qualitatively distinct from the soliton-like processes. The above-mentioned lasers have a constant cavity length so that each spectral component of the pulse propagates the same distance. By contrast, the fibre lasers with the distributed mirrors have different distances for different spectral components of the pulse. Both experimental observations and theoretical results show that the gain of the laser plays a critical role in the steady-state pulses. Therefore, the pulse-shaping in the DUF fibre lasers dominates from the gain and loss processes (i.e., dissipative processes) in addition to the phase modulations, which is different from the large normal dispersion lasers where the spectral filtering effect plays a key role. In addition, the spectral width of the DUF laser is less than 1 nm, which is much narrower than that of large normal dispersion lasers.

Figure 6 shows that although the two separated sidebands have different wavelengths with a difference of 2.6 nm, their fundamental harmonic frequencies are the same as the fundamental cavity frequency (i.e., $5.731817$ MHz). In fact, the experimental observations show that all sidebands in Fig. 6(a) have the same fundamental harmonic frequency, i.e., the same round-trip time of 174.46475 ns (i.e., reciprocal of $5.731817$ MHz of fundamental harmonic frequency).
The total length of the linear laser cavity is approximately 17.7 m. The EDF and SMF of standard single-mode fibre (SMF). The EDF provides the gain amplification for the lasers. The experimental setup for the laser cavity is shown in Fig. 1(a). The conceptual model of the fibre laser is presented in Fig. 1(b). The laser set-up and experiments are used to measure the laser output performances. Measurement method. To confirm the pulse characteristics, we numerically simulate the pulse formation of the proposed laser. The numerical modelling includes the physics terms such as the group velocity dispersion of fibre, the self-phase modulation, the dispersion of the LCFBG, and the gain of the EDF. Because the spectral width of the pulses is much narrower than that of the gain and the LCFBG, the spectral filtering effect is ignored in the modelling. Therefore, we use the nonlinear Schrödinger equation to describe the pulse propagation in the laser oscillator, i.e.,

\[
\frac{\partial A}{\partial z} + \frac{1}{2} \left( g A + |A|^2 A \right) = \frac{\partial^2 A}{\partial t^2} + \frac{1}{2} g + \frac{1}{2} g \right) \left( A + \sqrt{n} |A|^2 A. \right. \tag{1}
\]

Here A, \(B_1, \) and \(\gamma \) denote the electric field envelope of the pulse, the fibre dispersion, and the cubic refractive nonlinearity of the fibre, respectively. The variables \(z \) and \(t \) represent the time and the propagation distance, respectively. \(g \) describes the gain function of the EDF and is expressed by \(g = g_0 e^{-E_0/E_F} e^{-\gamma z^2/2}, \) where \(g_0, \) \(E_0, \) and \(E_F, \) are the small-signal gain coefficient related to the doping concentration, the pulse energy, and gain saturation energy that relies on pump power, respectively. The theoretical modelling here is different from that in the previous reports \(^{2, 5}, 14, 21, \) i.e., the spectral filtering term is excluded in Eq. (1), whereas it is included in the latter. Based on a two-level saturable absorber model \(^{14, 21}, \) the intensity-dependent absorption coefficient is given by \(\beta = \beta_0 + \beta_1 (1 + \sqrt{\frac{n}{n_0}}) \), where \(\beta_0, \beta_1, \) and \(n_0, \) are the linear limit of saturable absorption, nonsaturable absorption, and saturation intensity, respectively. To numerically simulate the properties and behaviour of the laser, the simulation is started from an arbitrary signal and converges to a stable solution after approximately 100 round trips. In the simulation, we use the following parameters to match the experimental conditions: \(g_0 = 6 \text{ dB/m}, E_{15} = 135 \text{ pJ}, \beta_1 = 11 \text{ ps/km and } \gamma = 1.8 \text{ W}^{-1} \text{km}^{-1} \) for EDF, and \(\beta_2 = 22 \text{ ps/km and } \gamma = 1 \text{ W}^{-1} \text{km}^{-1} \) for SMF. The parameters of SWNT-SA are set as the values measured \(^{2, 14}, \) i.e., \(\beta_0 = 12.05 \% \), \(\beta_1 = 87.87 \% \), and \(n_0 = 9.67 \text{ MW/cm}^2\).

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Acknowledgments
This work was supported by the National Natural Science Foundation of China under Grants 10874239, 10604066, and 61123007.

Author contributions
X.L. proposed the laser system, completed the numerical simulation, and wrote the main manuscript text. Y.C. performed the main experimental results. D.H. performed part simulation. X.Y. prepared part figures. Z.S. contributed to the scientific discussion. All authors contributed to the scientific discussion. All authors discussed the results and substantially contributed to the manuscript.

Additional information
Supplementary Information accompanies this paper at http://www.nature.com/scientificreports

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Liu, X., Cui, Y., Han, D., Yao, X. & Sun, Z. Distributed ultrafast fibre laser. Sci. Rep. 5, 9101; DOI:10.1038/srep09101 (2015).

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