Coherent Expansion of a Gain-Switched Optical Frequency Comb Employing a Dual-Stage Active Demultiplexer

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Abstract *We experimentally demonstrate a novel expansion architecture for a gain-switched laser, based on simultaneous injection-locking of multiple modes of a gain-switched Fabry-Perot laser, using a dual-stage active demultiplexer. A 6.25 GHz expanded comb with a spectral bandwidth over 875 GHz (expansion factor ~10) is presented.*

Introduction

An optical frequency comb (OFC) is a laser source comprising equidistant and phase correlated lines. Such properties make the OFC invaluable in a wide range of applications such as spectroscopy [1], atomic clock [2], steganography [3], spectrally efficient optical communication [4]-[6], photonic millimetre (mmW)/ terahertz (THz) generation [7], [8], and many more.

The optimum characteristics of an OFC depend on the target application [9]. However, most OFCs would need to portray a minimum set of requirements such as a large number of lines, a high degree of phase correlation, low noise (phase and intensity), and tunability in free spectral range (FSR) and emission wavelengths. Amongst several semiconductor-based OFC generation schemes, an externally injected gain-switched laser (EI-GSL) offers simplicity, tunability, and cost-effectiveness [6]. However, the number of OFC lines generated is limited by the restricted modulation bandwidth of the semiconductor laser used. To address this challenge, several photonically integrable expansion schemes have been investigated, including the use of electro-optic phase modulators [6], cascaded gain-switched Fabry-Pérot (FP) lasers [10], dual-mode FP lasers [11], and mutually injection-locked GSLs [12]. These schemes are effective but limited to an expansion factor of up to 3.

In this work, we propose a novel technique for the coherent expansion of an EI-GSL by externally injecting a gain-switched FP laser with two tones demultiplexed from a source OFC. This results in the generation of a comb spaning across six FP modes with an expansion factor of 10. We also demonstrate that optimisation could be carried out to generate a flat OFC with a bandwidth of 300 GHz (suited for communications) or a wide OFC with a spectral bandwidth of 875 GHz (for mmW/THz generation). The comb bandwidth is determined by ensuring that all lines within that span can be actively demultiplexed. Finally, we show that the lines from the expanded OFC portray a low optical linewidth of ~85 kHz (transferred from the master laser) and have a correlated phase noise (produce a beat tone linewidth of 13 Hz). It is important to note that the proposed architecture lends itself to photonic integration and to the best of our knowledge, delivers the broadest gain-switched OFC to date.

Principle of operation: OFC generation and expansion

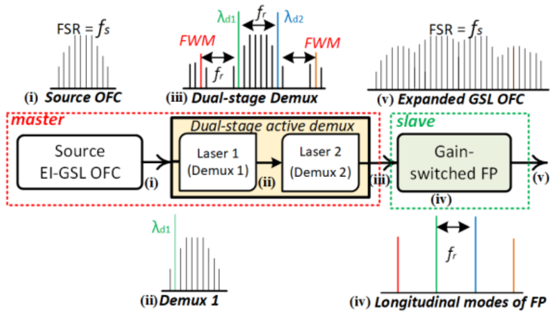

Fig. 1 Principle of operation of proposed expanded gain-switched OFC generation scheme. Insets (i)-(v): represent spectral line graphs at each stage

The proposed architecture, depicted in Fig. 1, is realised using a master-slave configuration, where the master (red rectangle) comprises a source OFC with an FSR of f_s. This OFC is first injected into a dual-stage active demultiplexer (DS-AD) [8], the output of which is subsequently injected into the slave (gain-switched FP laser). The working principle and detailed characterisation of the DS-AD can be found in [8]. It enables the selection/ demultiplexing of two OFC tones (λ_{d1} and λ_{d2}) with the desired frequency separation (f_r). In this experiment, the separation is matched to that of the longitudinal mode spacing of the FP slave laser used. Here, the strong injection of Demux 1 into Demux 2, results in four-wave mixing (FWM) inside the cavity of Demux 2 leading to the generation of new spectral components that are separated from λ_{d1} and λ_{d2} by f_r [13]. Thus, as illustrated in Fig. 1(iii), the output of the DS-AD contains two demultiplexed and amplified OFC tones, and newly generated FWM tones. Next, the output of the DS-AD is injected into an FP slave laser that is gain-switched at f_s. The demultiplexed OFC lines and the FWM components simultaneously injection lock adjacent longitudinal modes of the gain-switched FP laser. The injection locking of multiple longitudinal modes of the FP results in the generation of a coherent wideband gain-switched OFC at FSR $of\ f_s$.

Experimental demonstration and discussion

The experimental setup of the proposed expansion scheme, comprising a source OFC followed by a DS-AD and a slave FP laser, is shown in Fig. 2(a). The source OFC is an EI-GSL as shown in Fig. 2(b), with an FSR of 6.25 GHz (f_s). It emits 13 coherent tones (within 5 dB from the spectral peak) spanning over 81.25 GHz. As highlighted in the principle of operation, the source OFC is then injected into a semiconductor laser-based DS-AD [8]. In this work, the DS-AD consists of two commercially available discrete mode (DM) lasers and two 3-port optical circulators (to enable optical injection) in series (the dotted red rectangle, Fig. 2(a)). Two OFC tones (20 dB below the spectral peak) separated by 150 GHz, are demultiplexed/amplified with the aid of the DS-AD. As mentioned above, new spectral components are formed due to FWM in Demux 2, as shown in the optical spectrum (red) in Fig. 2(c). These amplified OFC and the FWM tones at the output of the DS-AD, act as a master signal.

A FP laser diode encased in a TEC-controlled butterfly package is used as a slave laser. It exhibits a threshold current (I_{th}) of 10 mA and is biased at 6× I_{th}, emitting an average output power of 8 dBm. The optical spectrum of the free-running FP laser is shown in Fig. 2(c) (black trace) and has a longitudinal mode spacing of ~160 GHz. The slave FP laser is then gain-switched at 6.25 GHz (with the same RF source used for the source OFC). Figure 2(c) (light-blue trace) shows the optical spectrum of the gain-switched FP laser, where the absence of discernible comb lines can be observed, owing to a large timing jitter due to the gain-switching process [14]. Subsequently, the output of the DS-AD is injected into the gain-switched FP laser, which results in injection locking of multiple FP

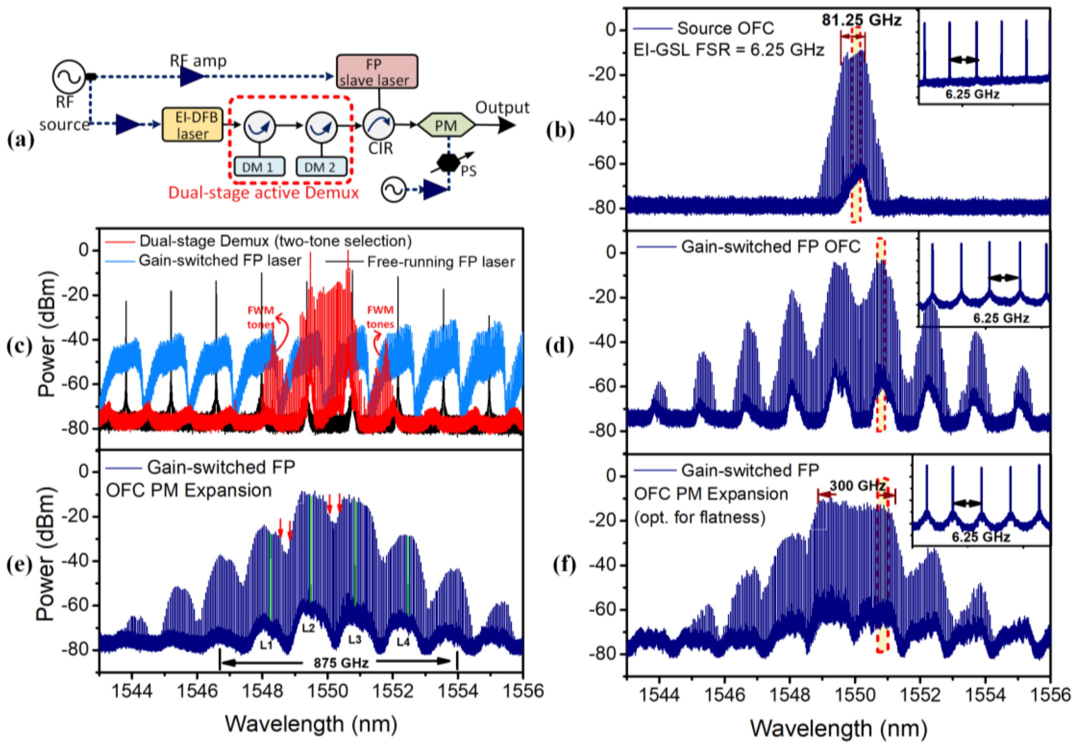

Fig. 2: (a) Experimental setup of proposed gain-switched OFC expansion scheme. Optical spectra of **(b)** externally injected gain-switched DFB laser with FSR of 6.25 GHz, **(c)** overlapped free-running FP slave laser (black), gain-switched FP laser at FSR of 6.25 GHz (cyan), dual-stage active Demux output enabling two- tone selection and FWM (red), **(d)** gain-switched OFC generation across 6 FP modes, **(e)** gain-switched FP OFC expansion via PM, and **(f)** optimised for flatness. Note: in **(e)** OFC lines L1 - L4 (marked in green) are picked for linewidth measurements. Lines between red arrows are chosen for phase correlation test. Here, EI-DFB: externally injection locked DFB laser, DM: discrete mode laser, PS: phase shifter.

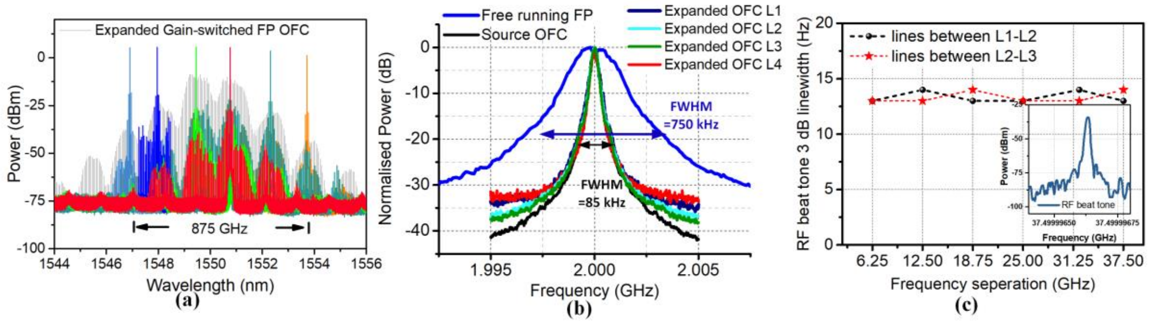

Fig. 3: (a) Optical spectra of active demultiplexed expanded OFC with various frequency separation, OFC characterisation results (b) linewidth (based on delayed self-heterodyne), and (c) phase correlation characterisation: RF beat tone measurement.

modes with the demultiplexed lines (corresponding to λ_{d1} and λ_{d2}) and FWM tones. The optical injection from the DS-AD locks the phase of the successive gain-switched FP pulses and introduces a pulse-to-pulse coherence [14], leading to the generation of discernible coherent OFC lines across several FP modes.

The strong injection from the DS-AD into the FP laser also stimulates the FWM process inside the FP cavity [13], which assists in the simultaneous locking of six gain-switched FP modes , as shown in Fig. 2(d). The output of the gain-switched FP OFC can be further expanded by passing it through a phase modulator ($V_\pi = 4\,V,$ driven with 13 V at 12.5 GHz) to achieve a gain-switched OFC spanning over 875 GHz, as shown in Fig. 2(e). In comparison to the source OFC, the generated gain-switched OFC is expanded by a factor of ~10. Furthermore, the expansion of the OFC can be optimised for flatness or/and wide span, according to the target application. To demonstrate this, the expansion is tuned to achieve a continuous flat OFC spectrum over 300 GHz (within 5 dB) with an optical carrier to noise ratio (OCNR) >50 dB, as depicted in Fig. 2(f). This is done by optimising the separation between the two tones used for injection locking the FP laser (f_r reduced by 25 GHz). Such an expanded comb, optimised for flatness, could be utilised for superchannel-based optical networks. On the other hand, the wider comb (875 GHz, Fig. 2(e)), may be employed for mmW/THz generation and spectroscopy applications. Furthermore, the bandwidth of the expanded OFC is demonstrated by demultiplexing lines from each of the six FP modes (including low power tones), using an active demultiplexer [15], as shown in Fig. 3(a).

A characterisation of the expanded GS-OFC lines is carried out in order to verify that the comb lines exhibit similar linewidth and are phase correlated. First, we filter an individual line from the source OFC and the free running FP laser and measure their linewidths as 80 kHz and 750 kHz, respectively (see Fig. 3(b)). Then, the linewidth of expanded gain-switched FP lines from each mode, as marked by green lines in Fig. 2(e), is measured to be 90, 85, 85, and 90 kHz (L1-L4). The reduction in the linewidths is a clear indication of the efficient phase noise transfer between the source and the expanded FP OFC. Furthermore, to verify the level of phase correlation between expanded OFC lines, a pair of tones from two different modes (marked by red arrows in Fig. 2(e)), separated by frequencies between 6.25 and 37.5 GHz, are filtered and their RF beat tone measured. The results are plotted in Fig. 3(c), showing a 3 dB beat linewidth of 13 Hz (inset in Fig. 3(c)), which clearly demonstrates a high level of phase correlation between the OFC lines.

Conclusions

We have experimentally demonstrated a photonically integrable expansion scheme for generating a wide bandwidth gain-switched OFC. The expansion results in 875 GHz spectral bandwidth with an expansion factor of 10. The extended OFC lines portray low linewidth and a high degree of phase correlation. Furthermore, we show that the using proposed method, the OFC can be optimised either for best flatness or maximum bandwidth, depending on the target application. Finally, by actively demultiplexing comb lines with various frequency separations, we showed that the proposed scheme is suitable for use in superchannel-based optical networks, for mmW/ THz generation and spectroscopy applications.

Acknowledgments

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