16 Wavelengths Comb Source Using Large-Scale Hybrid Photonic Integration

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Abstract: We demonstrate a 16 wavelengths comb source using hybrid integration of 16 gain chips, 32 balls lenses and an arrayed waveguide grating, with total output power >20 mW, SMSR > 56 dB, and kHz-scale linewidths.

1. Introduction

Integrated comb sources offer the opportunity to generate many wavelengths of continuous-wave light from a single photonic circuit as opposed to aggregating together multiple lasers with single output wavelength. This solution can be used in many optical systems based on wavelength-division-multiplexing (WDM), but it is particularly attractive for architectures where the multi-wavelength laser can be remote or disaggregated [1,2] from the high-speed WDM modules or chiplets to meet stringent requirements of energy efficiency and high capacity.

Here, we demonstrate a comb source with 16 wavelengths with 100 GHz spacing using large-scale, hybrid integration of 16 gain chips, 32 ball lenses and an arrayed waveguide grating (AWG). Other multi-wavelength laser sources based on similar lasing architectures have been shown on monolithic indium phosphide platforms [3], however a comb source with this design and with many channels was never demonstrated before using hybrid photonic integration. Furthermore, thanks to our low loss platform and the long lasing cavity, our laser source achieves high total optical output power (>20 mW), high side mode suppression ratio (SMSR> 56 dB), and output channels with linewidths on the kHz-scale and lower.

2. Design and Packaging

Figures 1(a-b) show a photograph of our comb source and a schematic of its architecture. It is composed by 16 III-V based gain chips integrated with a passive silica-on-silicon chip by means of 16 pairs of ball lenses (32 in total). The gain chips have high-reflection (HR) coating on the back facet and anti-reflection (AR) coating on the front facet to form reflective semiconductor optical amplifiers (RSOAs). The RSOAs are placed on a 750 μm pitch and are bonded to a silicon submount with metal contacts. Furthermore, the RSOAs are wire-bonded to a printed circuit board that allows to control individually their electrical currents [not shown in the photograph of Fig. 1(a)]. Optical coupling between each RSOA and the optical waveguides on the silica chip is achieved through a pair of ball lenses: the first lens is made in LaSFN9 (n = 1.81) and is used to collimate the light at the RSOA output, the second one is made in silica (n = 1.45) and is used to refocus the light to the optical waveguides on the silica chip. Additional

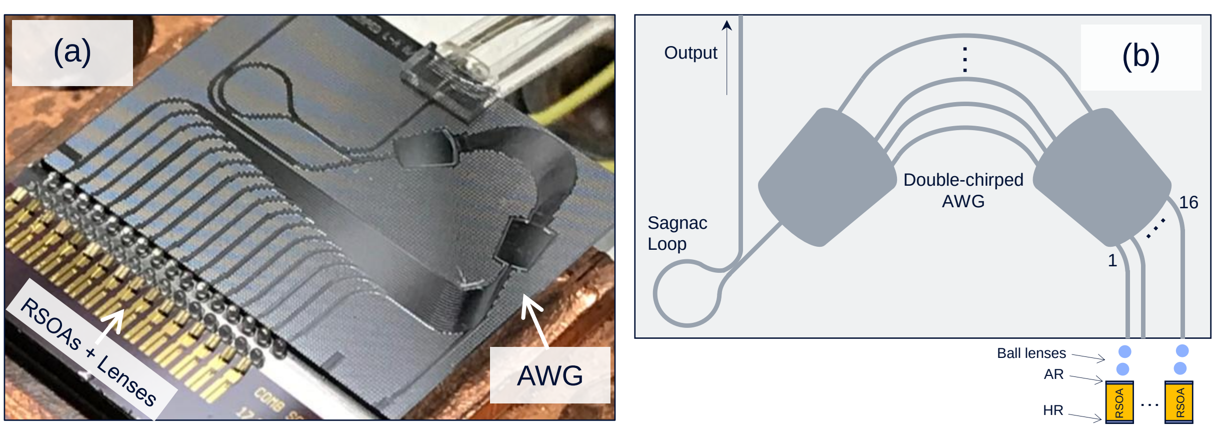

Fig. 1. (a) Photograph of the 16 wavelengths comb source that integrates 16 RSOAs, 32 ball lenses and double-chirped AWG. (b) Schematic of the comb source architecture.

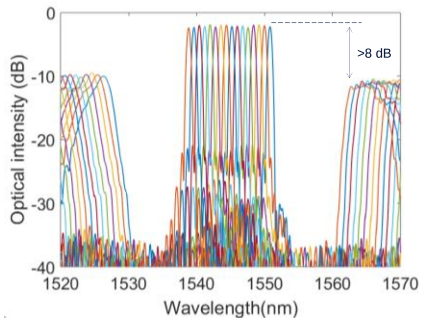

Fig. 2. Measured transmission passbands of a 16 channels double-chirped AWG with same design as that used in the assembled comb source of Fig. 1(a).

details on this coupling scheme can be found in [4]. The lenses are aligned and glued in place by a semi-automated setup, that was developed at Nokia Bell Labs, and that allows to perform automatic packaging (alignment, attachment, and curing) of each ball lens.

The silica chip hosts a 16×1 AWG, made with waveguides of 2% refractive index contrast, and a Sagnac loop that behaves as a partial reflector. A fiber pigtail is glued to the output waveguide of the chip for optical output [top-right corner of Fig. 1(a)]. Each passband of the AWG selects a narrow wavelength range from the broadband optical emission of the RSOAs. A laser cavity is formed between the HR back facet of each RSOA and the Sagnac loop for a total of 16 integrated laser cavities. Lasing occurs at wavelength within the passbands of the AWG.

In order to ensure monomode emission on every channel, the AWG uses a particular design, usually referred to as "double-chirped" design [5], which enables to have a dominant passband for every channel, and suppresses the transmission passbands of other free-spectral ranges (FSR) of the AWG. This is achieved by chirping the lengths of the waveguides of the array and the angular distribution of the waveguides on the star couplers. Figure 2 shows the measured transmission of the 16 channels of a double-chirped AWG, nominally identical to that used in the assembled comb source of Fig. 1(a). Our design allows to suppress the passbands in other FSRs by more than 8 dB. The maximum insertion loss of the AWG channels is 2.4 dB when light is coupled in and out with standard single mode fibers. The passbands have bandwidth at -1 dB of about 44 GHz and channel spacing of about 100 GHz.

3. Experiments

Figure 3 shows the optical intensity at the output of the comb source measured when all the 16 channels are lasing at the same time. The comb source spectrum was measured with an optical spectrum analyzer with 0.01 nm resolution bandwidth and is here normalized to the optical power at the wavelength of maximum transmission. The total output optical power P_{out} is about 13.2 dBm, as measured on an optical power meter. The SMSR is larger than 56 dB for all the 16 channels. In Fig. 3 the 16 RSOAs were biased with different current levels to equalize the output power of the channels as much as possible, from a minimum of 75 mA for channels 5 and 13, to a maximum of 170 mA for channel 9. This biasing condition of the 16 RSOAs corresponds to a total electrical power dissipation of about 2.46 W. Channels are here numbered from the longest wavelength to the shortest, in such a way that channel n. 1 has the longest wavelength and channel n. 16 has the shortest. All measurements shown in this work were performed with a fiber-optic isolator placed at the output fiber of the module and at the constant temperature of 20˚C ensured by a

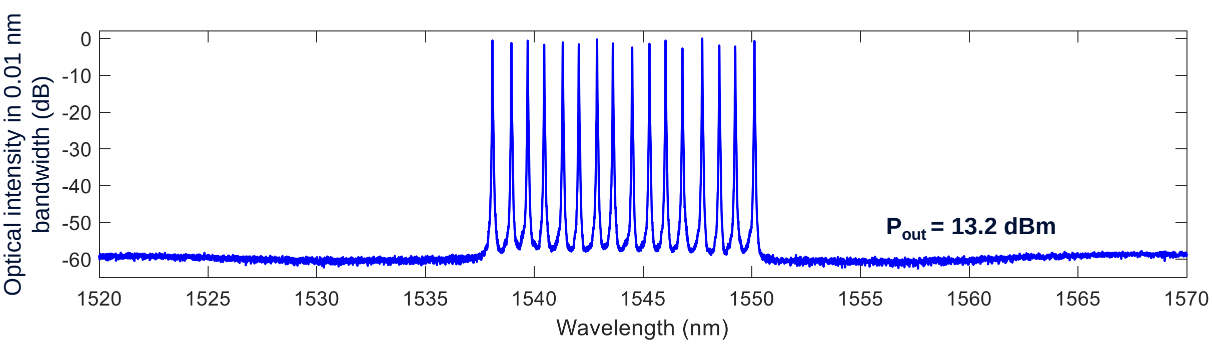

Fig. 3. Optical intensity of the comb source measured versus wavelength with all the 16 channels active simultaneously. The total optical power coupled to the output fiber of the comb source module is P_{out} = 13.2 dBm.

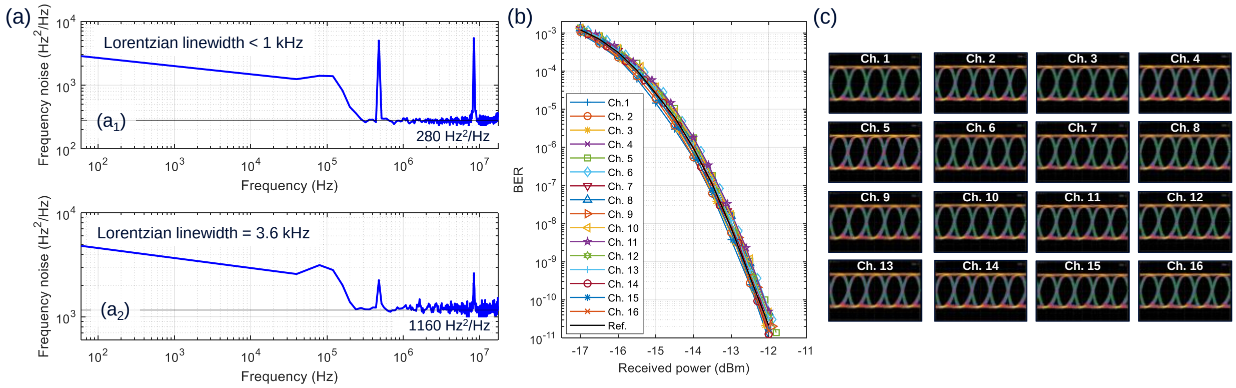

Fig. 4. (a) Power spectral density of the frequency noise for channels with (a_1) narrowest and (a_2) widest Lorentzian linewidth. Measured (b) BER and (c) eye diagrams at 25 Gbit/s NRZ-OOK when the continuous-wave output wavelengths of the comb source are modulated with a lithium niobate modulator. The black solid line in (b) is the BER of a commercial tunable laser added for reference.

thermo-electric cooler packaged under the assembled comb source of Fig. 1(a).

Note that, in this prototype, the “best” channel can provide maximum output power of about 6 mW (channel n. 11) and the “worst” channel can provide maximum output power larger than 2 mW (channel n. 9), when the current on the RSOAs is varied in the range from 0 to 200 mA. The threshold current for lasing varies from a minimum of 22 mA to a maximum of 46 mA across the 16 channels of the comb source. This variability among the RSOAs used in this work is primarily caused by the different gain due to the yield of the fabrication process.

Also, we measured the linewidth of all the 16 channels of our comb source module using a delayed self-heterodyne method with acousto-optic modulator and digital signal processing. Figures 4(a_1-a_2) show the power spectral density of the frequency noise of the channels with narrowest and widest linewidths (respectively channel 1 and 10). At high frequency, the white noise level is about 280 Hz^2/Hz and 1160 Hz^2/Hz in the two cases, which correspond to a Lorentzian linewidth lower than 1 kHz for the best channel [Fig. 4(a_1), channel 1] and of about 3.6 kHz for the worst channel [Fig. 4(a_2), channel 10]. The other fourteen channels have Lorentzian linewidths between these two values. The spurious narrow-band peaks in the frequency spectrum of Figs. 4(a_1-a_2) are due to our experimental setup.

Finally, to confirm even further the potential of our comb source, we modulated its continuous-wave output wavelengths at 25 Gbit/s non-return-to-zero on-off-keying (NRZ-OOK) using a commercial lithium niobate modulator. Figures 4(b-c) show bit-error-ratio (BER) and eye diagrams of all the 16 channels of the module when turned on and modulated individually one at a time. For a fair comparison, the RSOAs were biased to provide the same optical power at the output fiber of the comb source (~0.8 dBm), and the modulator was always driven with the same bias and drive voltage. Erbium-doped fiber amplifier, passband filter and variable optical attenuator were used before the photodetector to vary the optical power at the receiver input and minimize the optical noise. Fiber optic isolator and polarization controller were used between the comb source and the lithium niobate modulator. As demonstrated in Fig. 4(b), all channels of our comb source have about the same performance, and provide the same BER/sensitivity of a commercial tunable laser, that was added for reference with black line in Fig. 4(b).

4. Conclusions

We demonstrated a 16 channels comb source through hybrid integration of 16 RSOAs, 32 ball lenses and silica double-chirped AWG. The total output power is larger than 20 mW and all linewidths are on the kHz-scale and lower.

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5. References

[1] M. Wade, E. Anderson, S. Ardalan *et al*., “An error-free 1 Tbps WDM optical I/O chiplet and multi-wavelength multi-port laser,” in Optical Fiber Communication Conference (OFC) 2021, OSA Technical Digest (Optical Society of America, 2021), paper F3C.6.
[2] B. Buscaino, E. Chen, J. W. Stewart, T. Pham and J. M. Kahn, “External vs. integrated light sources for intra-data center co-packaged optical interfaces,” Journal Lightw. Technol. **39**, 1984-1996 (2021).
[3] M. Zirngibl, “Multifrequency lasers and applications in WDM networks,” IEEE Communications Magazine **36**, 39-41 (1998).
[4] Y. Gao, C. Bolle, Y. Low, R. Papazian, M. Cappuzzo, B. Keller, F. Pardo, and M. P. Earnshaw, “Hybrid integration with efficient ball lens-based optical coupling for compact WDM transmitters,” IEEE Photon. Technol. Lett. **28**, 2549-2552 (2016).
[5] C. R. Doerr and C. H. Joyner, “Double-chirping of the waveguide grating router,” IEEE Photon. Technol. Lett. **9**, 776-778 (1997).