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Isolator-free > 67-GHz bandwidth DFB+R laser with suppressed chirp

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Abstract: We report on simultaneous realization of > 67 GHz bandwidth, a reflection tolerance up to 12.5 %, and a record-low chirp parameter of 0.6 for a DFB laser integrated with a passive waveguide with 3% reflection coating, called DFB+R laser.

OCIS codes: (250.5960) Semiconductor lasers; (060.4510) Optical communications

1. Introduction

Directly modulated lasers (DMLs) have recently entered a new era in terms of high speed performance, enabled by the use of the optical cavity to enhance the modulation bandwidth. In 2016, we reported a modulation bandwidth (BW) of 55 GHz for short-cavity distributed reflector (DR) laser with a gain length of 50 μm [1]. The device was designed to harness strong detuned-loading effect [2], photon-photon resonance (PPR) effect [3], and in-cavity FM-AM conversion effects [4]. In September 2019, a DR laser with a gain length of 50 μm was fabricated by NTT, using a membrane structure bonded on SiC substrate. This structure realized a strong vertical optical confinement with the air on the top and SiC at the bottom, located only ~ 0.1 μm away from the MQW region [5]. As a result of the strong optical confinement in the vertical direction, the relaxation oscillation frequency (F_r) was enhanced to 40 GHz. The optical feedback from an integrated passive waveguide with 30% reflectivity created a photon-photon resonance at 95 GHz which extended the modulation BW to 107 GHz. Transmission of 239.3 Gb/s was demonstrated using PAM4 signaling with 101-tap linear and 61-tap nonlinear equalizers. The fiber coupled power was 0.8 mW and a praseodymium-doped fiber amplifier (PDFA) was necessary to reach +6 dBm required for the use of a hard-decision (HD) FEC for a bit error rate (BER) of 3.8×10^{-3}. However, the use of PDFA is prohibitively expensive in realization of > 200 Gb/s transmission systems.

Also, in September 2019, we reported a gain-switched pulse generation at 50 GHz repetition rate using a DFB laser integrated with a passive waveguide [6]. At the end of the waveguide, we have applied 3% reflection in order to simultaneously generate PPR effect, detuned-loading effect, and in-cavity FM-AM conversion effect. We call this design a DFB+R laser. It was shown that those BW enhancement effects are still beneficial under gain-switched operation with a large modulation current (~ 120 mA peak to peak). Recently, we also demonstrated a net rate of 200-Gb/s Nyquist PAM8 over 10 km of a standard single-mode fiber (SSMF) with 9 ps/nm dispersion at 1315 nm. This was achieved using a short-cavity DBR laser with a modified DBR grating and a low chirp parameter of 1.0. [7].

In this paper, we report on a 3-dB BW approaching to 75 GHz for a DFB+R laser [6], exhibiting a record-low chirp parameter of 0.6. Furthermore, we report isolator-free operation for all the three DML designs: namely, DR laser in ref. [1], DBR laser in ref. [7], and DFB+R laser in this paper. The advantages of DFB+R laser are: 1. fabricated on reliable InP substrate, 2. close similarity to production design of DFB laser, 3. simple single-contact device, 4. high yield similar to DFB lasers, 5. low cost and small size (200 μm), 6. high output power (> 20 mW), 7. wide BW (~ 75 GHz), 8. low operation bias (65 mA for 75 GHz and 11 mA for 45 GHz), 9. isolator-free, 10. low chirp parameter (0.6) comparable to those for electro-absorption modulator lasers (EMLs). Using a packaged DFB+R laser, a back-to-back line rate of 411.6 Gb/s (net bit rate of 337.5 Gb/s) and 314.9 Gb/s over a 10-km SSMF were achieved in a dual-subcarrier entropy loading scheme [8].

2. DFB+R laser design and principle of high-speed operation

The device structure and the operation principle are shown in Figs. 1. The DFB length is 80 μm and the integrated passive waveguide length is 120 μm. At the end of the passive waveguide, 3% mirror coating was applied. This forms an in-cavity etalon filter between the DFB grating and the 3% reflection. Fig. 1(b) in red shows the reflection profile of such in-cavity etalon filter. The ripples can be maximized with ~ 3% coating. Note that the lasing mode is located at the steep slope of a ripple. A strong detuned-loading effect can be produced at this mode position due to the conversion of the blue chirp to a negative cavity loss. In comparison, the case for AR coating on the passive waveguide is also shown in blue. In this case, a smooth stopband of DFB grating can be seen. In contrast, in passive

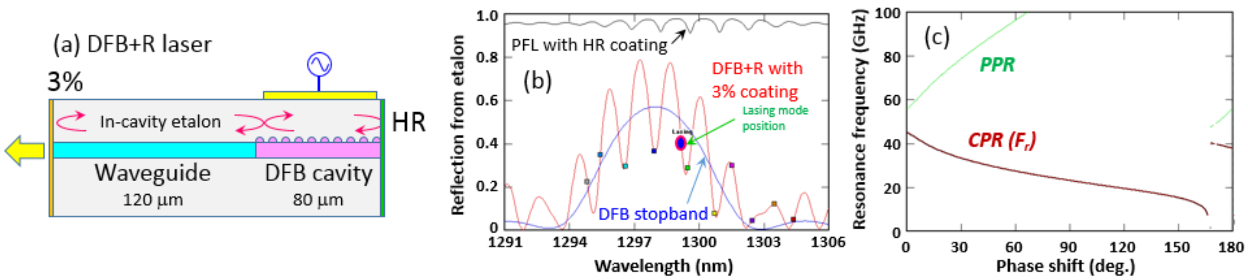
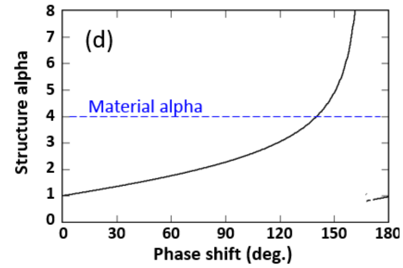


Fig. 1(a) Schematics of DFB+R laser, (b) in-cavity etalon profile for DFB+R with 3% coating (red), passive feedback laser with HR coating (black), and the stopband of the DFB section (blue), (c) Carrier-photon resonance (CPR) frequency (or Fr) and PPR frequency calculated as a function of phase tuning of feedback light, (d) structural alpha parameter simulated for DFB+R laser.



feedback laser (PFL), HR coating was applied at the end of the waveguide [9]. The PPR effect created a response peak at 35 GHz due to the HR coating. However, F_r was only 12 GHz. This may be due to a lack of detuned-loading effect in PFL with HR coating. Indeed, an etalon filter with an HR coating acts as a Gires–Tournois (GT) interferometer (or all-pass filter), and the reflection can be always close to 100% (Fig. 1(b) black). Therefore, the detuned-loading effect vanishes with HR coating. Fig. 1(c) shows the simulated F_r and PPR frequency by LaserMatrix [10]. As the phase condition changes, for example by thermal tuning of the wavelength of DFB laser with changing the bias, F_r can be increased to 40 GHz, which is more than a factor of 2 enhancement compared to our regular DFB lasers [11]. Simultaneously, PPR frequency reduces to 60 GHz. Therefore, a standard 25-Gb/s rated DFB laser can be turned into a 65-GHz DFB+R laser by simply applying a 3% reflection coating.

3. Principle of structural alpha parameter reduction and isolator-free operation

The principle of the chirp parameter reduction was discussed in 1988 in the context of the detuned-loading effect [12]. The frequency blue chirp can be converted into the reduction of the mirror loss in the etalon or DBR mirrors. This can effectively enhance the differential gain, and therefore, in turn, reduces the structural alpha parameter [10]:

$$\alpha_e = \frac{\frac{d}{dN}\mathrm{Re}(\Omega)}{\frac{d}{dN}\mathrm{Im}(\Omega)} = \frac{\mathrm{Im}\left[\tilde{\Gamma}_z(1+i\alpha)\right]}{\mathrm{Re}\left[\tilde{\Gamma}_z(1+i\alpha)\right]} \quad , \quad (1)$$

where N is the carrier density, Ω is the complex oscillation frequency, α is the material linewidth enhancement factor and $\tilde{\Gamma}_z$ is the complex reactive fill factor of the active section. For a DBR laser, $\tilde{\Gamma}_z = L_a / \left(L_a + \tilde{L}_p\right)$, where L_a is the length of the active region and $\tilde{L}_p$ is the complex length of the Bragg section. This term is related to the chirp and the slope of the etalon filter (or detuned-loading effect). The simulation of the structural alpha parameter is shown in Fig. 1(d). The material alpha parameter is assumed to be 4. The smallest structural alpha parameter of 0.95 is expected when F_r is maximized due to the enhanced effective differential gain. The reduction of the effective alpha parameter can increase the reflection tolerance since it is inversely proportional relation with the alpha parameter squared, according to Eq. 10 in [13]. This means that the reflection tolerance is expected to improve by 15 dB for a structural alpha parameter of 1.0. However, isolator-free operation has not been reported experimentally in the past. This is probably because standard DBR lasers cannot produce a strong enough detuned-loading effect.

4. Laser characteristics

The measured light-bias current characteristics for DFB+R laser are shown in Fig. 2(a). The output powers at 25 °C and 50 °C were 23.6 mW and 15 mW, respectively. Such a high power operation is important for realizing > 200-Gb/s WDM unamplified system where a fiber coupled power close to 10 dBm is required. The high power operation is an advantage of the DFB+R laser over the DR laser, where power is limited by the shorter active length of ~ 50 µm necessary to avoid the mode hop, and maximizing the detuned-loading effect.

Fig. 2(b) shows the measured S21 responses of the DFB+R laser. Conventional PN blocking in buried-hetero (BH) structure was used as described in ref. [11]. RC cutoff frequency was around 22 GHz. F_r was enhanced to 40 GHz and PPR was observed at 65 GHz at a bias of 65 mA, realizing a 3-dB BW approaching 75 GHz. The BW is maximized at a bias slightly below the kink where the mode hop happens. Another kink is observed at 13 mA at 25 C. Just below this kink, a 3-dB BW of 45 GHz is obtained at only 11 mA. At 50 °C, a 3-dB BW of 57 GHz was obtained. Higher

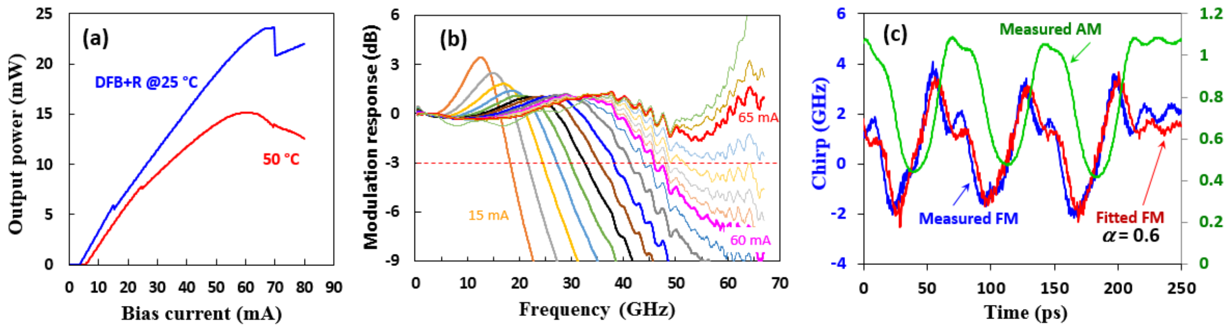
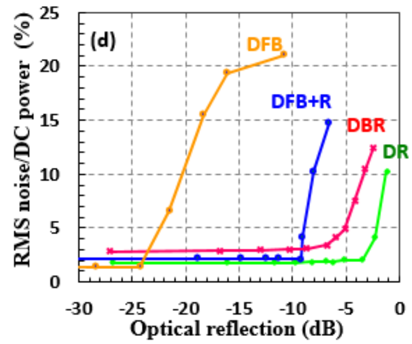


Fig. 2(a) L-I characteristics for DFB+R laser at 25 C and 50 C, (b) small signal modulation response measured with Keysight N5227A PNA Microwave Network Analyzer (67 GHz BW),(c) AM and FM waveform at 25 Gb/s NRZ from Keysight M8196A 92-GSa/s Arbitrary Waveform Generator. Fitted alpha parameter was 0.6 for DFB+R laser, (d) RMS noise under optical reflection for DFB+R (blue) laser, modified DBR laser (red), DR laser (green), and conventional DFB laser (orange).



reflection coating than 5% degrades the side mode suppression ratio and also degrades the longitudinal fill factor of the reactive photons. Therefore, the coating around 3% is the optimum. The chirp parameter was extracted by fitting to the measured FM waveform based on AM waveform [11]. Fig. 2(c) red shows the AM waveform of 25 Gb/s NRZ signal generated by an arbitrary waveform generator (Keysight M8196A 92-GSa/s). The measured chirp waveform shows a very small chirp of ~ 6 GHz including both transient and adiabatic chirp components in spite of high speed rise/fall times of ~ 12 ps. The extracted chirp parameter is 0.6. This is record-low for DMLs and comparable to that for EMLs.

To study the reflection tolerance, Fig. 2(d) shows the root mean square (rms) photocurrent noise measured under DC operation as a function of the power of the feedback light. Without optical feedback, the rms photocurrent noise was around 3%, and the corresponding RIN was -155 dBc/Hz. For DFB+R laser, the noise suddenly increased under -9 dB reflection. Here the tolerance is translated to the case of 2 dB coupling loss. It is interesting to note that the DR laser reported earlier [1] showed even higher reflection tolerance of -4 dB. The modified DBR laser in ref. [7] showed a reflection tolerance of -7 dB when the measured alpha parameter was 1.0. The DFB+R laser is advantageous for high-speed due to the high longitudinal filling factor close to unity for the reactive photons. However, in terms of the reflection tolerance, a DR laser with lower longitudinal filling factor (~ 65%) is a better design. In all cases, isolator-free operation is realized according to 802.3bs IEEE specification.

5. Conclusions

DFB+R laser exhibited a high output power (>20 mW), wide 3-dB BW (> 67 GHz), record-low alpha parameter (0.6), isolator-free operation. Separately, we have demonstrated a back-to-back line rate of 411.6 Gb/s (net bit rate of 337.5 Gb/s) and 314.9 Gb/s over a 10-km SSMF at 1313 nm [8].

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