Discussion on the improvement of opto-RF link properties by using a cascade laser source.

Frédéric Dross, Frédéric van Dijk and Philippe Gallion

Abstract

We have studied the possible RF link properties improvement that can stem from electrically cascading several laser sources and combining the light from each source into a single information-carrying light beam.

The effect of carrier recyling is first studied within a discrete architecture consisting of n individual laser diodes macroscopically connected in series. We find an RF link gain improvement proportional to n^2 and a link noise figure improvement proportional to n. The model is validated by experimental data. The architecture nonetheless carries some drawbacks including the need for a zero-loss optical combining device to benefit from the RF link gain improvement, and some bandwidth shortcomings.

We then study the effect of carrier recycling within an integrated laser device, a so-called bipolar cascade laser. In order to push back on the limitations of the discrete architecture, the device consists of n active regions integrated into a single laser cavity. We apply a rate equation model to this promising structure and find that, in good agreement with previously published results, the external efficiency is expected to increase by a factor of n, leading to a possible RF link gain improvement by a factor of n^2. Because the laser noise is dominated by the photon corpuscular noise, however, we expect only weak influence of electrically cascading active junctions into a single laser cavity on the laser intensity noise and thus on the link noise figure, in contrast to what is widely believed but has never been demonstrated experimentally.

Index Terms

opto-RF link, analog optic transmission, laser diode, bipolar cascade diode, RF link gain, RF noise figure

I. INTRODUCTION

In present radar systems, there is a need for few-hundred-meter analog information transmission links between the remote microwave antennas and the centralized numerical information processing calculator. For this several-gigahertz-bandwidth radiofrequency information transmission, optical fiber links present numerous advantages over coaxial radio-frequency (RF) links, in terms of modulation bandwidth, attenuation, weight, volume and electromagnetic immunity which are key issues for airborne or space applications. However, in today's short distance transmission systems, analog data is usually transmitted via coaxial-cable-based RF links. The cost-effective opto-RF links actually still suffer from a low RF link gain. For instance, for a 1.55 μm transmission link, if we assume typical values for the opto-electronic compoments of the link (i.e. respectively 0.15 W/A and 1 A/W for the DFB laser and for the photodiode external efficiencies, and respectively 50% and 10% input and output optical fiber coupling, and 2 dB optical absorption losses), we find a RF link gain equal to -27.3 dB. Figure 1 displays the distribution of the RF power loss during transmission. The electrical-to-optical conversion efficiency is the major loss factor. In order to overcome this limitation, one solution consists in using n laser sources and collecting the light from each laser into a single photoreceiver [1]. One electron flowing through the cascaded structure can give birth to one photon at each step, thus increasing by a factor of n the quantum electron-to-photon efficiency.

Another limitation of opto-RF links is the high noise figure, attributable to the high intensity noise of the laser source. Once again, using the combination of the light beams from several lasers enables averaging the optical intensity noise. When the optical noises from all the laser sources are not correlated, the overall relative intensity noise can be decreased by a factor of n [2], [3], [4].

A discrete laser architecture carries some drawbacks in terms of space, alignment costs and achiveable frequency bandwidth. A monolithic bipolar cascade laser has been also proposed as an integrated version of the discrete architecture [5], [6]. It consists of several active regions monolithically stacked and electrically connected via highly-doped backward-biased tunnel junctions. Due to its compactness, this device is expected to overcome all the drawbacks listed above. Despite theoretical studies on the subject [4], no experimental demonstration of link gain improvement nor of noise figure improvement has been published so far. In order to shed light on this ambiguity, we propose a very comprehensive rate equation-based model that describes the electro-optic laser behavior, and that highlights the basic and intrinsic differences between a standard single-active-region semiconductor laser and a monolithic bipolar cascade laser.

In the first part of this paper, we describe in detail the intrinsic reasons why it is possible to improve the RF link properties by using several discrete lasers. We present theoretical models of our experimental results and of previoulsy published results on cascade laser sources composed of several discrete lasers. In the second part, we describe the comprehensive Langevin rate equation model for the simulation of the monolithically integrated bipolar cascade laser source. We then examine whether a link gain improvement and/or a noise figure improvement is still possible with an integrated device that will preserve good modulation bandwidth properties.

II. Improving the RF link properties by using several discrete lasers

A. Theoretical framework

We consider an opto-RF link composed of a laser source, an optical fiber, and a photoreceiver. The specificity of the link considered here lies in the laser source. It is composed of several discrete laser diodes whose output beams are combined. For the sake of clarity, we will only derive the calculation for a source consisting of two laser diodes. A schematic representation of the combined source is depicted in figure 2.

The electrical RF output power P_{out} at the end of the link is carried by the modulated current flowing across the photoreceiver $\hat{I}$ (the hat represents the peak modulation amplitude). Assuming perfect impedance matching between the photoreceiver and the RF waveguide following the device, we have:

$$P_{\mathrm{out}} = \frac{1}{2} R \hat{I}^2, \tag{1}$$

where R is the loading impedance of the photodiode (usually taken as 50 Ω for large bandwidth applications).

Considering the optoelectronic devices operating in their linear range, since the light collected is the combination of the individual laser beams, we write the RF output power as:

$$P_{\mathrm{out}} = \frac{1}{2} R \eta^2 \hat{I}_{\mathrm{las}}^2 \left(\eta_1 \eta_{\mathrm{opt1}} + \eta_2 \eta_{\mathrm{opt2}}\right)^2. \tag{2}$$

Since the lasers are connected in series, the same current modulation $\hat{I}_{\mathrm{las}}$ flows across all the individual lasers. η_i is laser i's electron-to-photon conversion efficiency. $\eta_{\mathrm{opt}i}$ is the optical transmission in the optical arm i and includes transmission losses, as well as losses in the combining device. η is the photodiode conversion efficiency.

Once again assuming no RF impedance mismatch, the RF input power (P_{in}) is directly related to the current modulation $\hat{I}_{\mathrm{las}}$ flowing into the laser combined source:

$$P_{\mathrm{in}} = \frac{1}{2} R_{\mathrm{s}} \hat{I}_{\mathrm{las}}^2. \tag{3}$$

R_{s} is the series resistance of the laser source.

We keep the same photoreceiver to allow the comparison between sources composed of one single laser and of several lasers. We also assume that the overall source impedance R_{s} does not significantly change with the number of cascaded lasers (when needed, it is still possible to add a discrete resistance to match the source impedance to the input waveguide characteristic impedance; R_{adapt} plays this role in figure 2). In these conditions, the RF link gain g is expected to follow the simple rule:

$$g = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \propto \left(\eta_1 \eta_{\mathrm{opt1}} + \eta_2 \eta_{\mathrm{opt2}}\right)^2 \propto 4 \eta_1^2 \eta_{\mathrm{opt1}}^2. \tag{4}$$

The last expression corresponds to the ideal conditions where the two optical arms and lasers are identical (i.e. $\eta_1 = \eta_2$ and $\eta_{\mathrm{opt1}} = \eta_{\mathrm{opt2}}$).

This first important result can be generalized easily for a source composed of n identical lasers connected in series. The RF link gain of the source is proportional to:

$$g = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \propto \left(\sum_i \eta_i \eta_{\mathrm{opt}i}\right)^2 \propto n^2 \eta_1^2 \eta_{\mathrm{opt1}}^2. \tag{5}$$

In typical opto-RF transmission links, under standard operating conditions, the noise figure is dominated by the laser source optical relative intensity noise (RIN, expressed in dB/Hz). Shot noise and thermal noise are therefore here assumed to be negligible. Under linear operation, the RIN of the laser source $\mathrm{RIN_s}$ is defined in an observation bandwidth Δf by [7]:

$$\mathrm{RIN_s} = \frac{\langle \delta S^2 \rangle}{\langle S \rangle^2 \Delta f} = \frac{\langle \delta I^2 \rangle}{\langle I \rangle^2 \Delta f}. \tag{6}$$

$\langle \delta S^2 \rangle$ and $\langle \delta I^2 \rangle$ are the mean square optical power and photodiode current fluctuations, and $\langle I \rangle$ and $\langle S \rangle$ are the average optical power and photodiode current. The second equality is valid for a quantum efficiency of the photodetector close to unity. In other words, the electrical noise is assumed to be a replica of the photon noise.

The RF output noise N_{out} observed on the receiver can be expressed as a function of the mean square current fluctuations, and thus of the laser source relative intensity noise:

$$N_{\mathrm{out}} = R \langle \delta I^2 \rangle = R \langle I \rangle^2 \mathrm{RIN_s} \Delta f. \tag{7}$$

In our setup, the rate of modulation remains the same. Therefore the output RF power P_{out} increases proportionally to the square of the output optical power $\langle S \rangle^2$. The output signal-to-noise ratio is then found to be proportional to:

$$\mathrm{SNR_{out}} = \frac{P_{\mathrm{out}}}{N_{\mathrm{out}}} = \frac{P_{\mathrm{out}}}{R \langle I \rangle^2 \mathrm{RIN_s} \Delta f} \propto \frac{\langle S \rangle^2}{\mathrm{RIN_s} \langle S \rangle^2} \propto \frac{1}{\mathrm{RIN_s}}. \tag{8}$$

Consequently, assuming a constant input signal and signal-to-noise ratio, the noise factor NF appears to be proportional to the RIN of the laser source:

$$\mathrm{NF} = \frac{\mathrm{SNR_{in}}}{\mathrm{SNR_{out}}} \propto \mathrm{RIN_s}. \tag{9}$$

As a result, for noise issues in the following discussion, we will be interested only in the relative intensity noise of the combined source and in its comparison with the RIN of each individual laser RIN_i.

It is possible to prevent any optical feedback using optical isolators and therefore we here assume no optically-induced noise cross-correlation nor multipath effects. In addition, the individual lasers are connected in series, which may trigger some electrical cross-correlation in the case of a voltage drive source [4]. Here, we also assume that no electrical correlation can take place due to the high ($\geq 50\ \Omega$) laser source impedance. Under these conditions, the noise intercorrelation between the optical power from laser i and laser j is as follows:

$$\forall i \neq j,\ \langle \delta S_i \delta S_j \rangle = 0. \tag{10}$$

We thereafter develop in equation 6 the current reaching the photodiode as originating from the combination of the individual laser light beams:

$$\begin{aligned} \mathrm{RIN_s} &= \frac{\langle \delta S^2 \rangle}{\langle S \rangle^2 \Delta f} = \frac{1}{\Delta f} \frac{\langle (\delta S_1 + \delta S_2)^2 \rangle}{(\langle S_1 \rangle + \langle S_2 \rangle)^2} \\ &= \frac{1}{\Delta f} \frac{\langle \delta S_1^2 \rangle + \langle \delta S_2^2 \rangle}{(\langle S_1 \rangle + \langle S_2 \rangle)^2} = \frac{\langle S_1 \rangle^2 \mathrm{RIN_1} + \langle S_2 \rangle^2 \mathrm{RIN_2}}{(\langle S_1 \rangle + \langle S_2 \rangle)^2}. \end{aligned} \tag{11}$$

B. Experimental results

In order to check the validity of the models described above, we have used four commercially available butterfly packaged lasers. We electrically connected them in series. Each packaged laser has a built-in 25 Ω series resistance, so that the overall resistance is close to 100 Ω. This high resistance implies some RF power reflections at the device interfaces, and thus a low absolute link gain value. In addition, the light of all lasers is gathered using an optical 4 by 4 coupler. This device introduces $\eta_{\mathrm{opt}i} = 6$ dB optical intrinsic losses on each arm. Nonetheless, we are here only interested in the improvement of the RF gain relative to the number of connected lasers. In order to preserve the same electrical mismatch and thus the same RF reflected power, we have disconnected the fibers of the unused lasers while performing link measurements involving only a subset of lasers. In addition, we circumvent the difficulty of the difference in transmission loss $\eta_{\mathrm{opt}i}$ of each arm i, and in the laser's efficiency η_i by performing the measurements for all configurations involving one, then two, and then three lasers. Each time, we calculate the "averaged" RF power by averaging the square root of the measured RF power and taking the square of this average value. These conditions are equivalent to the ideal conditions where the four arms are balanced, and the last expression in equation 5 applies.

We inject $P_{\mathrm{in}} = 0$ dBm at frequency $f_0 = 80$ MHz to the composed source already biased with a 80 mA DC current. We then measure the output RF power P_{out} and obtain the RF link gain for all configurations. The average absolute value of the RF link gain for the configuration involving only one laser was found to be $g(1) = -46$ dB. This value is very low. However, the intrinsic optical attenuation of the coupler already reduces the RF link gain by a factor $\eta_{\mathrm{opt}i}^2 = 12$ dB. Without this additional intrinsic loss, the measured RF link gain is within the usually observed range of opto-RF link gains.

In figure 3, we report the improvement of the measured link gain as a function of the number of lasers connected. The agreement between our measurements and the values calculated from equation 5 appears to be very good. We also report the measurements performed by Cox *et al.* with the same setup [1]. Their results also perfectly match the expected behavior, proving that it is possible to improve the RF link gain by cascading several discrete laser sources.

In order to check the combined-source RIN model (equation 11), we have used two of the same commercially available DFB lasers; we connected them in series and gathered the light via a 2 by 2 optical coupler. Using a polarization controller we inject the light in crossed polarization in order to prevent any heterodyne beating between light beams. The RIN measurements are then carried out over a large bandwidth (100 MHz-21 GHz). For each frequency, we compare the measured RIN of the individual lasers, the measured RIN of the combined source and the RIN calculated with equation 11 fed by optical power and RIN measurements of the individual lasers. Measurement and calculation data are displayed in figure 4. The perfect agreement with the experimental data validates the calculation of equation 11 for two lasers. By comparing these results with RIN measurements obtained with two lasers independently biased, we have also checked that the electrical series configuration did not bring any observable noise correlation when the laser source impedance was close to 50 Ω. As an additional validation, for their 6-laser cascade device, Cox *et al.* also reported a 6 dB noise figure improvement that has to be compared to the 7.8 dB expected from equation 11 if the different arms were perfectly balanced in terms of optical power as well as intensity noise. These experiments directly prove the possible RIN, and thus noise properties improvement by cascading several discrete laser sources.

As a consequence of these very encouraging demonstrations of performance improvements in cascade sources using discrete lasers, much hope has been put into monolithically integrated series connected Bipolar Cascade Lasers (BCLs) for improving the RF link gain as well as noise properties. Nevertheless, until now, despite theoretical studies [4], [8] and device fabrication [6], no experimental link gain improvement nor noise reduction has been demonstrated for monolithically integrated BCLs. The following section is dedicated to the description of a comprehensive model of the dynamic behavior of such lasers.

III. Integrated monolithic bipolar cascade laser

A. Model presentation

The Langevin rate equation model we have used is based on the reservoir representation detailed in [7]. The rate equations describe the number of particles available in the carrier reservoirs and in the photon reservoir.

Our intention is to study the frequency response and noise properties of monolithic bipolar cascade lasers with multiple active regions, and to compare these with the characteristics of single-active-region, multiple-quantum-well lasers. Since the BCL device consists of n active regions, we allow the carrier populations N_i in the different active regions i to fluctuate separately. Nonetheless, once again for the sake of understandability, we will only derive the calculation for $n = 2$ active regions. The monolithic BCL under study consists then of two active regions of one quantum well, and the single-active-region laser has two quantum wells. In addition, a single-mode operation is required for efficient use in systems. Therefore, the photon reservoir is described by a unique number of particles P:

$$\frac{dN_i}{dt} = \frac{I}{e} - G_0\left(N_i - N_0\right)P - \left(AN_i + B\left(N_i\right)^2 + C\left(N_i\right)^3\right); \tag{12}$$

$$\frac{dP}{dt} = \left\{G_0\left(N_1 + N_2 - 2N_0\right)\right\}P + \beta B\left(\left(N_1\right)^2 + \left(N_2\right)^2\right) - \frac{P}{\tau_P}. \tag{13}$$

In order to keep the Langevin rate equation model as simple as possible and to put the emphasis on the most intrinsic influence of monolithically cascading several active regions, we neglect every second-order effect (e.g. carrier injection efficiency, non-linear gain, etc.). e is the electric charge; G_0 is the optical gain which is assumed to be linear; N_0 is the carrier density at transparency; A, B, C are respectively the spontaneous recombination coefficient, the bimolecular recombination coefficient and the Auger recombination coefficient; β is the portion of spontaneously emitted light coupled into the lasing mode; τ_P is the photon lifetime in the cold cavity. In the calculation, we also supposed that the bimolecular recombination was dominating relative to the other recombination processes: $A = C = 0$.

In order to study the dynamic behavior, we consider the small signal response to a harmonic excitation and linearize the resulting rate equations:

$$\begin{aligned}\frac{d}{dt}\Big(\delta N_i(t)\Big) &= \frac{\delta I(t)}{e} - G_0\left(\overline{N}_i - N_0\right)\delta P(t) \\ &\quad - \left(G_0\overline{P} + \frac{1}{\tau_E}\right)\delta N_i(t) + F_{N_i}(t);\end{aligned} \tag{14}$$

$$\frac{d}{dt}\Big(\delta P(t)\Big) = G_0\overline{P}\left(\sum_i \delta N_i(t)\right) + F_P(t). \tag{15}$$

$\overline{N}_i$ and $\overline{P}$ are the steady-state population resulting from the calculation of the solution of equations 12 to 13 under steady-state. $\delta N_i(t)$ and $\delta P(t)$ stand for the deviation of the population a time t from the average population. $F_{N_i}(t)$ and $F_P(t)$ are the langevin forces related to the carrier population i and to the photon population. $\frac{1}{\tau_E} = A + 2B\overline{N}_i + 3C\overline{N}_i^2$ is the slope of the recombination term as a function of the carrier population.

As a mathematical manipulation, we consider the total carrier population in the structure $N_+ = N_1 + N_2$ as a new variable. The separate fluctuations can still be found by considering the difference between the carrier populations. Equation 15 can then be written in a 2-by-2-matrix form:

$$\begin{pmatrix} G_0\overline{P} + \frac{1}{\tau_E} + i\omega & \frac{1}{\tau_P} \\ -G_0\overline{P} & i\omega \end{pmatrix}\begin{pmatrix} \delta N_+(\omega) \\ \delta P(\omega) \end{pmatrix} = \begin{pmatrix} \frac{\delta I(\omega)}{e} + F_{N_+}(t) \\ F_P(t) \end{pmatrix}. \tag{16}$$

The first matrix is the transfer function of the system. The source is composed either of intentionally modulated current, or noise-originating population fluctuations. We do not take into account the electrical correlation that may take place between the active regions [4]. This electrical correlation can only degrade the BCL's RIN as compared to the single-active-region laser RIN.

The analytical result comes immediately:

$$\delta P(\omega) = \frac{H(\omega)}{\omega_R^2}\left\{\omega_R^2\tau_P\left(\frac{\delta I(\omega)}{e}+F_{N_+}(\omega)\right)+\left(\frac{2}{\tau_R}+i\omega\right)F_P(\omega)\right\}, \text{ where} \tag{17}$$

$$H(\omega) = \frac{\omega_R^2}{\omega_R^2-\omega^2+2i\frac{\omega}{\tau_R}}, \tag{18}$$

$$\omega_R^2 = \frac{G_0\overline{P}}{\tau_P}, \text{ and} \tag{19}$$

$$\tau_R = \frac{2\tau_E}{G_0\overline{P}\tau_E+1}. \tag{20}$$

The average values used for calculating the dynamic behavior are the result of the steady-state solutions of equations 12 and 13.

The output power fluctuations are given by:

$$\delta S(\omega) = \eta_o\delta P(\omega) + F_S(\omega). \tag{21}$$

η_o is the proportionality constant between the photon population and the output power, F_S is the Langevin force related to the output power.

B. Opto-RF link gain improvement

For the calculation of the RF gain improvement, we are only interested in the intentional current modulation. For the 2-active-region BCL, the frequency response can be written as:

$$\frac{\delta S}{\delta I}(\omega) = 2\eta_0\frac{h\nu}{e}H(\omega). \tag{22}$$

The transfer function H gives the frequency dependence of the modulation response. The factor 2 is specific to our 2-active-region monolithic BCL case and it is easy to see that the intrinsic frequency response can be generalized for a n-active-region BCL to:

$$\frac{\delta S}{\delta I}(\omega) = n\eta_0\frac{h\nu}{e}H(\omega). \tag{23}$$

The low-frequency external efficiency is thus expected to increase linearly with the number of active regions. This feature is indeed characteristic of the carrier recycling process occurring in BCL, and is quite usually observed [9], [10]. Although very simple, our model is compatible with the experimentally reported behavior of monolithic BCLs. In addition, since the RF link gain is proportional to the square of the laser external efficiency, the use of a n-active-region BCL would result in a RF link gain improved by a factor of n^2. The RF link gain improvement is expected to be similar to the one observed for the discrete-architecture cascade laser described earlier in this article.

For a more realistic study, we need to take into account the parasitic impedance effect on the frequency response. This is obtained by convoluting a low-pass parasitic RC filter to the intrinsic frequency response:

$$\frac{\delta S}{\delta I}(\omega) = 2\eta_0\frac{h\nu}{e}H(\omega)\frac{1}{1+i\omega R_pC_p}. \tag{24}$$

R_p and C_p are the parasitic series resitance and capacitance of the device. Since the evolution of the parasitic capacitance cannot be forseen easily, we leave it equal for both structures. As for the series resistance, we add an estimated value of 5 ohms to the BCL series resistance in order to take into account the tunnel junction resistance.

We compare on figure 5 the frequency response of the single-active-region laser and of the bipolar cascade laser. The result is normalized to the low frequency response of the single-active-region laser.

The slight decrease in the 3 dB-bandwidth observed for the BCL is due to the increase of parasitic resistance. The response increase (by 3 dB) at low frequency for the BCL is directly related to the external efficiency increase discussed earlier (see equation 23).

As a conclusion, our simple rate equation model takes into account carrier recycling and forsees a RF gain improvement proportional to n^2 for monolithically integrated bipolar cascade lasers. This gain improvement is not limited in frequency by intrinsic phenomena, but only by the parasitic impedance that stems from a more complex technological process. Technological improvement (such as reducing the tunnel junction backward resistance) can therefore theoretically lead to a BCL frequency bandwidth comparable to a single-active-region laser. The reason why experimental RF link gain improvement has not yet been reported does not seem to be intrinsic, but lies more probably in the technological difficulties of obtaining a single-lasing-mode monolithic BCL.

C. RIN improvement

For the calculation of the RIN improvement, equation 21 relates the intrinsic fluctuations of the output power in the frequency domain. We multiply by the complex conjugate term and take the ensemble average, which gives, according to the Wiener-Khinchin relations, the spectral density of the output power noise [7]. Dividing the spectral density by the squared average output power, we eventually obtain the RIN defined by equation 6:

$$\mathrm{RIN}(\omega) = \frac{\eta_0^2}{\overline{S}^2}\frac{|H(\omega)|^2}{\omega_R^4}\left\{a_1 + a_2\omega^2\right\} + \frac{D_{\mathrm{SS}}}{\overline{S}^2},\ \text{where} \tag{25}$$

$$a_1 = \tau_P^2\omega_R^4 D_{\mathrm{NN}} + 4\frac{\tau_P}{\tau_R}\omega_R^2 D_{\mathrm{NP}} + 4\frac{1}{\tau_R^2}D_{\mathrm{PP}} \tag{26}$$

$$+2\frac{1}{\eta_0}\tau_P\omega_R^4 D_{\mathrm{NS}} + \frac{1}{\eta_0}\frac{2}{\tau_R}\omega_R^2 D_{\mathrm{PS}},\ \text{and} \tag{27}$$

$$a_2 = D_{\mathrm{PP}} + 2\frac{1}{\eta_0}\tau_P\omega_R^2 D_{\mathrm{PS}}. \tag{28}$$

The parameter a_1 prevails mainly at low frequency, whereas a_2 dominates the RIN at high frequencies.

The Langevin diffusion coefficients D_{XX} are calculated following [7]. Each energy exchange between the different reservoirs exhibits a random white noise with a variance equal to the average particle flow (Poissonian process). The population of carriers and photons are correlated by the coupled Langevin equations. These correlations tend to decrease the overall output power noise and are taken into account by the cross-correlation diffusion Langevin coefficients D_{XY}.

For the multiple-active-region case, a carrier recombining in the first active region will almost directly be available for recombination in the second active region. If we consider that the carrier reservoirs constitute a single reservoir, we can state that photons are created in the first active junction without loss of carriers available in the reservoir. On the one hand, this tends to decrease the carrier generated noise D_{NN}. On the other hand, it also weakens the carrier-photon relaxation mechanism D_{NP} which tends to decrease the overall optical noise. Because the comparison is held for an equal photon density in the unique laser cavity, the noise originating from photon mechnisms D_{PP} remains unchanged. We present in table I the diffusion coefficients calculated for the single-active-region and for the bipolar cascade multiple-active-region lasers. n_{sp} is the inversion population factor. $\widetilde{N}$ (respectively, $\widetilde{P}$) stands for $\overline{N}_+$ (respectively, $\overline{P}$) in the single-active-region laser and for $\overline{N}_+/2$ (respectively $\overline{P}/2$) in the bipolar cascade laser.

Although the Langevin forces have comparable magnitude, due to their respective prefactor in equation 25 they do not have the same influence on the calculated RIN. To illustrate this fact, we compare in figure 6 the complete RIN as calculated by equation 25, with the contribution to the RIN of D_{PP} alone. In order to do so, we artificially set D_{NP}, D_{NN}, D_{PS} and D_{SS} to zero and plot the resulting RIN contribution of D_{PP} at high (a_1 is also set to zero) and low (a_2 is in this case set to zero) frequency.

It is obvious from figure 6 than only the photon reservoir noise plays a decisive role in the RIN calculation. As the BCL and single-active-region structures are compared with equal photon density, the photon reservoir noise is the same and the RIN is not improved by monolithically cascading junctions.

Here for the first time, it is ex[plained that the reason why no RIN improvement has been reported so far using a BCL, appears to be a more fundamental issue. The only way to reduce the RIN is then to optically separate the active regions into uncoupled laser cavities (which is the case in theoretical studies claiming a possible RIN improvement [4]), but then all the benefits from integrating the device into a single component (in terms of space, fiber alignment and bandwidth) are lost.

IV. Conclusion

We have studied the influence of cascading active regions on two important link parameters: the RF link gain and the noise factor. We first have explained in detail that by using a laser source composed of n discrete lasers connected in series it is possible to improve the RF link gain by a factor of n^2 and the RIN by a factor of n. The result of the calculation has been confirmed by experimental measurements (with $n = 4$ for link gain measurements, and $n = 2$ for RIN measurements). In order to benefit entirely from the gain improvement, a zero-loss optical combining device is required.

We have also developed a model based on a rate equation analysis to compare the dynamic behavior of a monolithically integrated bipolar cascade laser and of a single-active-region laser. The model forsees no intrinsic bandwidth limitation and an RF gain improvement similar to the discrete architecture case. However, because the noise mainly arises from Poissonian-like photon particle-noise, the effect on the RIN of cascading active junctions in the same optical cavity is very weak.

As a consequence, according to our calculation, link noise improvement can only be achieved using a source of several separately oscillating laser cavities. A discrete architecture is suitable in this regard, but requires a zero-loss optical combining device to benefit from the RF gain improvement and is limited in terms of maximum bandwidth. A monolithic single-cavity bipolar cascade laser enables RF gain improvement over a large bandwidth, but does not result in a lower relative intensity noise.

Although much hope is usually put in integrated bipolar cascade lasers for reducing the noise in opto-RF links, our calculation forsees that cascading active regions in a single cavity will lead to a very weak effect on the RIN. The improvement is nevertheless still substantial on the RF link gain ($g \propto n^2$) and monolithic single-cavity bipolar cascade lasers still warrant some development effort.

ACKNOWLEDGMENT

The authors are thankful to Nakita Vodjdani, Mehdi Alouini and Clément Thibon for technical support and fruitful discussions.

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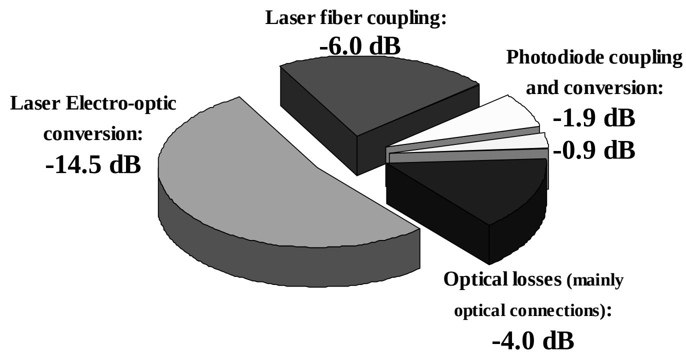

Fig. 1. Distribution of the 24.5 dB RF power loss during a signal transmission with an opto-RF link.

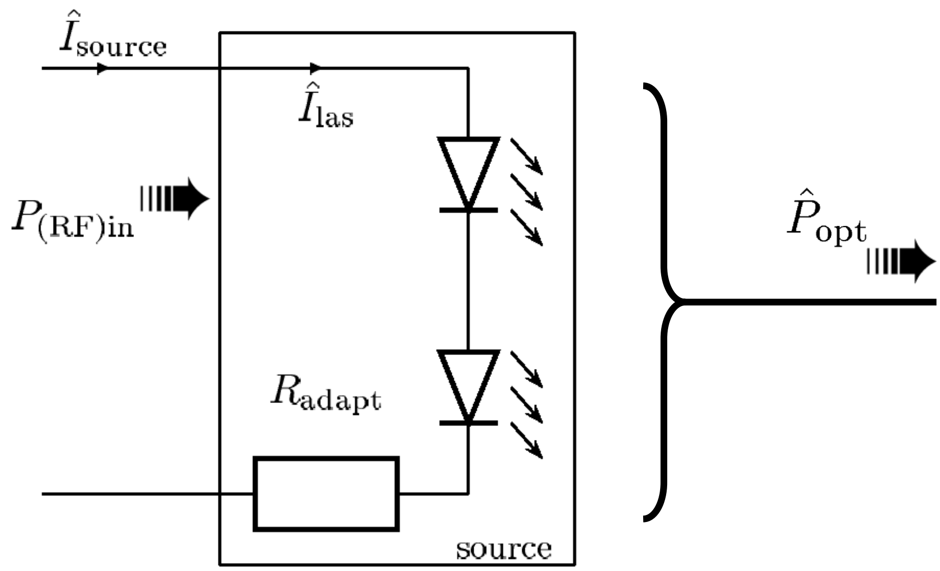

Fig. 2. Schematic of a combined laser source composed of two discrete laser diodes.

Langevin noise forces	Expressions	BCL structure	Reference structure
D_{NN}	$\frac{\overline{I}}{e} + \frac{\widetilde{N}}{\tau_E} + (2n_{\text{sp}} - 1)\frac{\widetilde{P}}{\tau_P}$	$8.0 \times 10^{17}\ s^{-1}$	$5.5 \times 10^{17}\ s^{-1}$
D_{NP}	$-(2n_{\text{sp}} - 1)\frac{\widetilde{P}}{\tau_P} - \beta\frac{\widetilde{N}}{\tau_E}$	$-3.0 \times 10^{17}\ s^{-1}$	$-1.5 \times 10^{17}\ s^{-1}$
D_{PP}	$2n_{\text{sp}}\frac{\overline{P}}{\tau_P} + \beta\frac{\overline{N}_+}{\tau_E}$	$4.0 \times 10^{17}\ s^{-1}$	$4.0 \times 10^{17}\ s^{-1}$

TABLE I

SUMMARY OF THE DIFFUSION COEFFICIENT ESTIMATED WITH THE SHOT NOISE LANGEVIN METHOD.

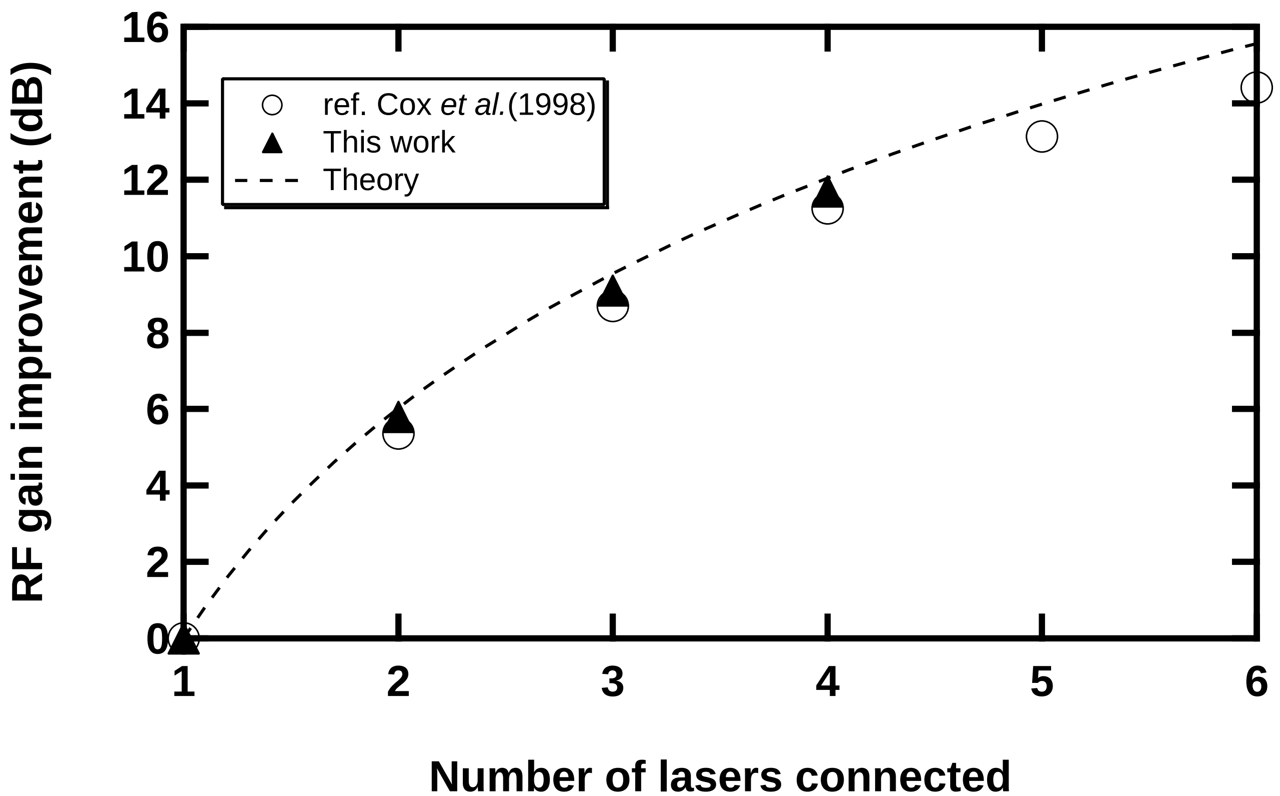

Fig. 3. Theoretical and experimental RF link gain improvement as a function of the number of lasers connected to the optical combining device.

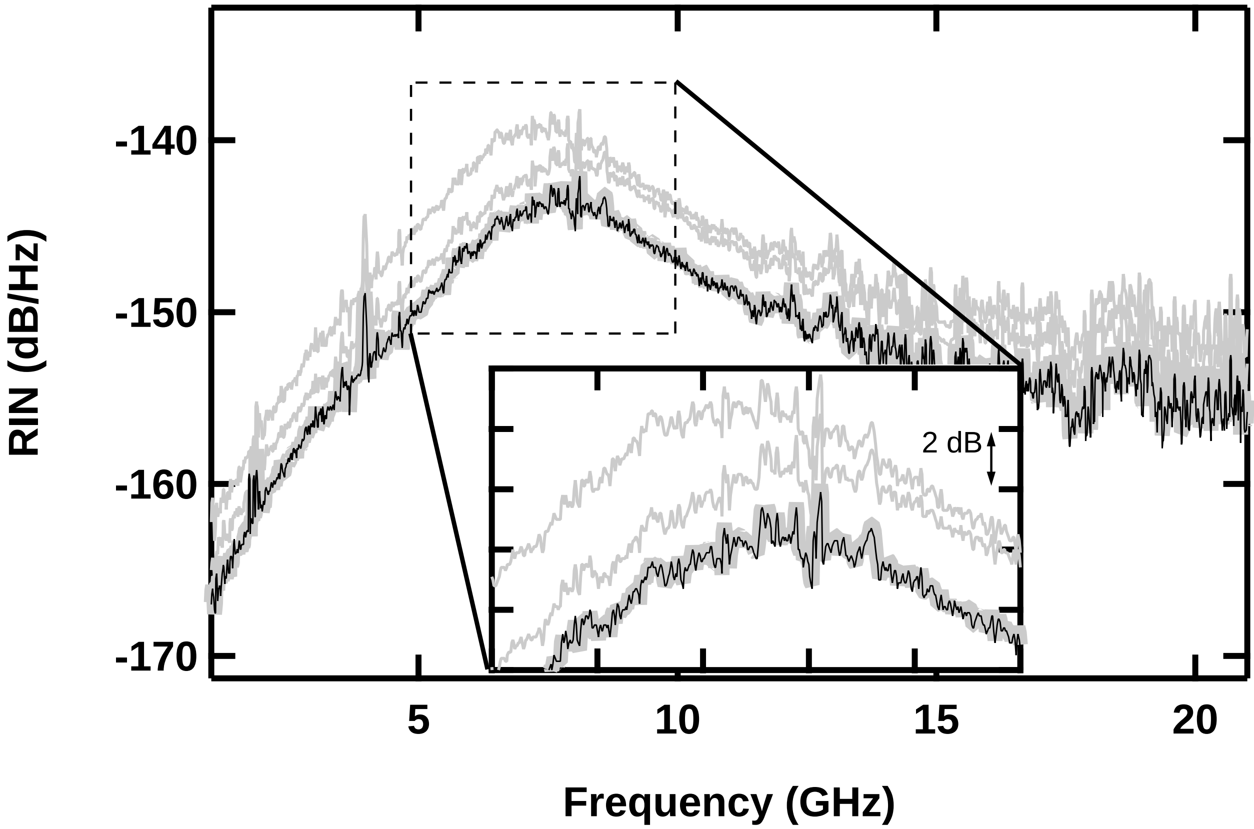

Fig. 4. Measured RIN of the combined source (thin black line) compared to the RIN of the discrete lasers composing the combined source (thin gray line) and expected combined source RIN calculated with equation 11 (bold gray line).

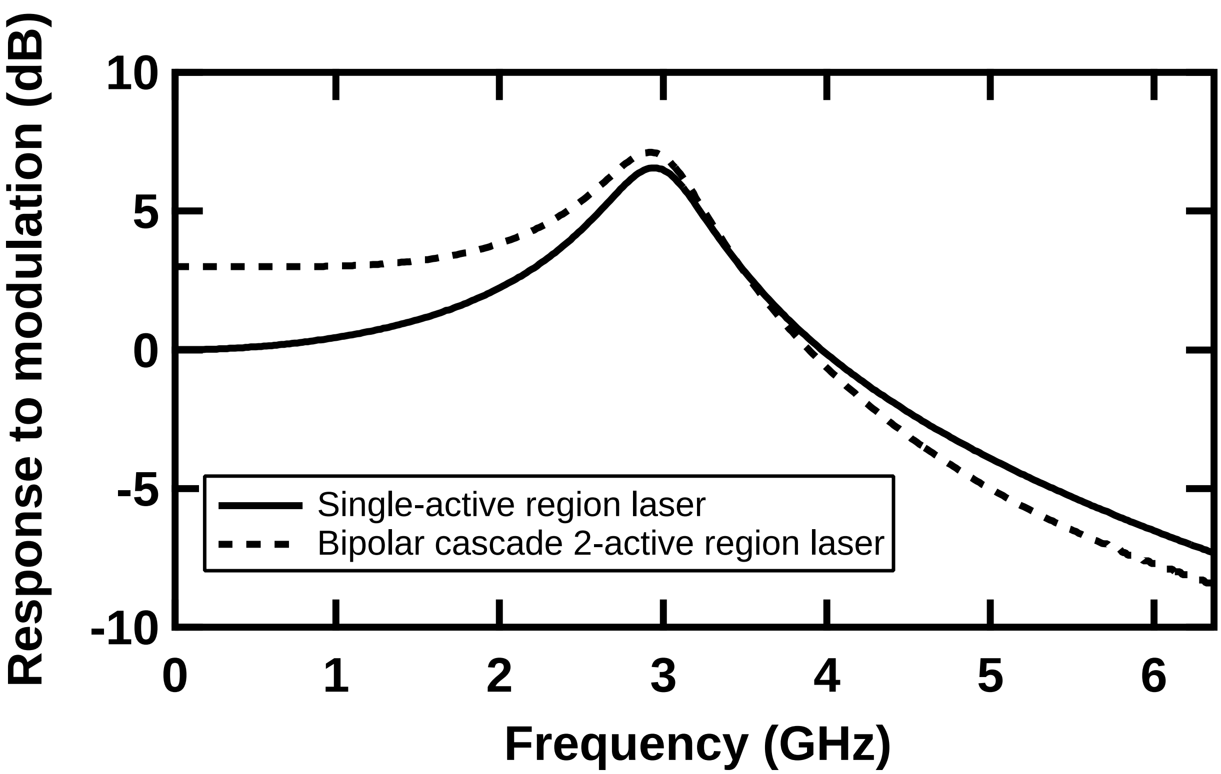

Fig. 5. Calculated spectral response to a current modulation of a 2-active-region bipolar cascade laser as compared to a single-active-region laser diode.

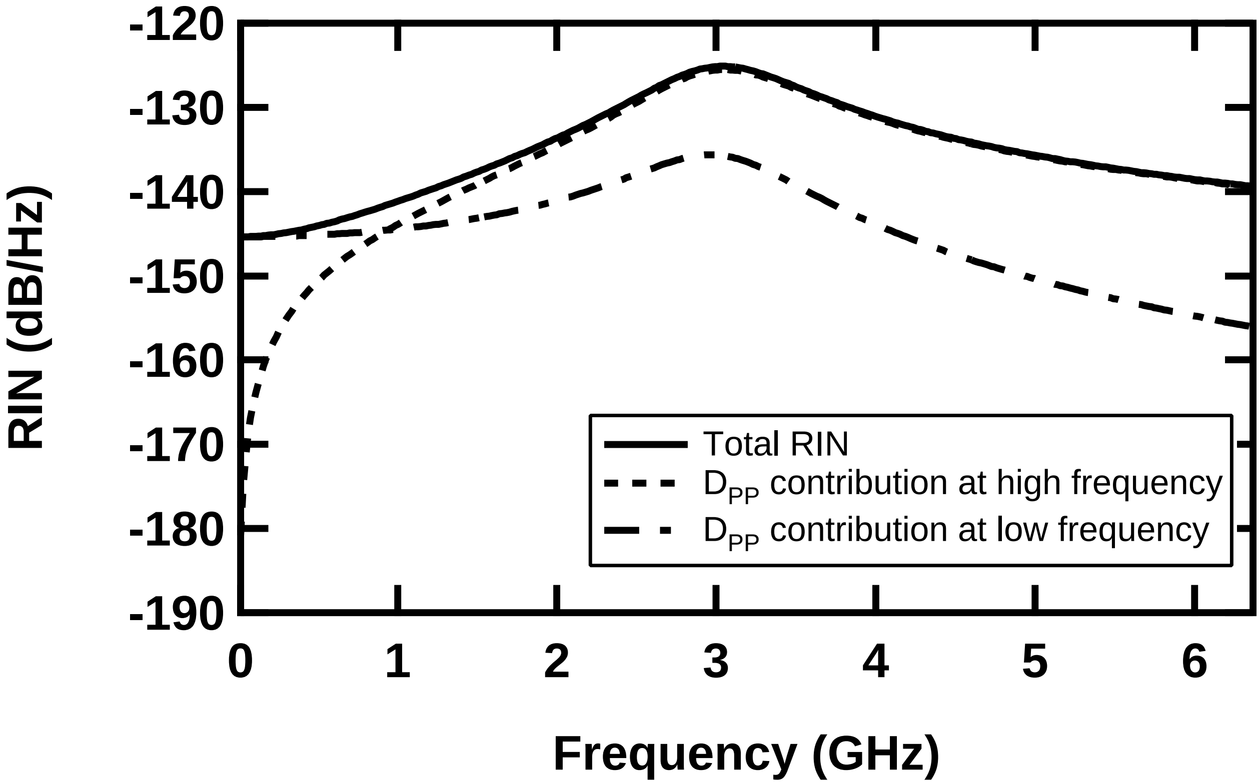

Fig. 6. Calculated RIN of a single-active-region laser and contribution of the photon population originating noise to the entire RIN.