Research article

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Electrically injected parity-time symmetric distributed feedback laser diodes (DFB) for telecom applications

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Abstract: The new paradigm of parity-time symmetry in quantum mechanics has readily been applied in the field of optics with numerous demonstrations of exotic properties in photonic systems. In this work, we report on the implementation of single frequency electrically injected distributed feedback (DFB) laser diodes based on parity-time symmetric dual gratings in a standard ridge waveguide configuration. We demonstrate enhanced modal discrimination for these devices as compared with index or gain coupled ones, fabricated in the same technology run. Optical transmission probing experiments further show asymmetric amplification in the light propagation confirming the parity-time symmetry signature of unidirectional light behavior. Another asset of these complex coupled devices is further highlighted in terms of robustness to optical feedback.

Keywords: complex-coupled laser diodes; Distributed Feedback lasers; optical feedback; parity-time symmetry.

1 Introduction

Controlling the electric permittivity along with the magnetic permeability has long been a major field of research in optics, especially in a magnetic perspective. With the design of artificial photonic materials, the precise control of the material parameters has led to the emergence of new functionalities in integrated optical devices. Photonic crystals and metamaterials represent the best known examples of the tailoring of, respectively, the electric permittivity and the magnetic permeability, inducing exotic wave-physics responses such as negative refractive index, negative permeability, photonic band-gap and zero refractive index.

On the other hand, in practice, the design and engineering of optical systems usually rely on the tailoring of not only the refractive index but also the amount of gain or losses. In particular, the presence of losses in too large amounts has long been considered to only cause degraded performance of optical systems. Thus, its use as a genuine tool in wave propagation remained unconsidered until recently (within a provision for a class of distributed feedback laser diodes that will be addressed below). Currently, a novel trend in modern optics consisting in the structured engineering of losses, balanced with gain and refractive index manipulation is receiving considerable attention from the photonics research community. This topic, originating from the so-called parity-time symmetry (PT-symmetry) inspired from the seemingly unrelated work of Bender et al. in 1998 [1] on the hermiticity of Hamiltonians, was found to be of great interest in several compartments of optics for the implementation of devices with intriguing light behavior. The transposition of PT-symmetry from quantum mechanics to optics, based on the equivalence between Schrödinger equation and the classical wave equation in coupled systems, revealed the potential interest of losses as an additional tool for the elaboration of exotic and intriguing functionalities in photonic circuits, such as unidirectional light transport, coherent perfect absorption or phase transition point to name but a few. Despite the broad interest brought by PT-symmetry and the opportunities it opens for photonic devices, its development has remained confined to demanding lab-level demonstrations, which although very

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interesting still remain far from real-world applications [2]. To the best of our knowledge, no spin-off to any "killer" application has yet taken place.

In the meantime, the sustained boom of optical telecommunications and optical fiber networks, spurred by the growth of the Internet traffic, Internet Of Things (IoT) or cloud data storage and computing, has increased the quest for efficient transmitters and coherent light sources, mostly laser diodes (LDs), offering robust operation against an ever broader range of excursion in their environment parameters. Those comprise basic ones such as temperature, but also lesser considered ones such as the capability to cope with coherent feedback, with its notoriously large capability to destabilize coherent emission from LDs. After decades of improvement of their static and dynamic performances, DFB laser diodes probably offer the best example of a multiply constrained optoelectronic achievement obtained from the sophisticated structural arrangement of materials with finely tuned properties (epitaxial stack and its doping profile, grating, electrical contacts, facet coating, and so on). Owing to their low cost, single-frequency operation, low power consumption and monolithic integration in some flavors of photonic integrated circuits (PICs), DFB lasers have become an industry standard equipment across virtually all data high-bit-rate transmission networks. As no new gain material could truly displace the incumbent GaInAsP alloys in DFBs in spite of many efforts (quantum dots, Raman, and so on), DFB improvements have been gradually more incremental. We notice however that as new avenues emerged, especially silicon photonics and its hybrid lasers, the longitudinal grating-based modal behavior has been a preferred focus [3] with the fate of "stored" photons remaining a key issue to tackle ultimate performances in various directions.

This work represents a combined attempt to revisit the longitudinal management of DFBs photons and to apply the concept of PT-symmetry to practical mature complex devices, in particular to the design and fabrication of an electrically injected single-frequency DFB laser. No such application to mature devices has been reported yet to the best of our knowledge. It must be recognized that the role of small amounts of gain or loss modulation along a DFB grating is a decades-old topic now, which started blossoming in the early 1990s before plummeting around 2000, as the need of coherent transmission temporarily faded owing to the advent of Erbium Doped Fiber Amplifiers (EDFA). A relatively complete account of the situation in 2005 can be found in [4] about the lasers with added gain coupling. During the next decade, the topic nearly stalled, and was only revived with the recent interest in PT-symmetry. Two noticeable limitations were natural along this stream: (i) the gain coupling was at most 10–20% of the index coupling, following the track initiated by Makino [5] and others [6, 7] that amounted to etch into multiple quantum wells (MQWs) to get the dual modulation; (ii) for somehow similar reason, the phase of the gain and index gratings was only π or 0. It thus remains to be investigated what can be gained by breaking these two limitations. Here, we shall mainly address the second one—essential to the PT-symmetry concepts—even though our technological developments could allow a larger amount of gain modulation than the above mentioned one.

Nevertheless, by attaining a gain/loss modulation regime where it substantially contributes to the overall feedback, we can better assess the issues at stake and the challenges raised by such a novel design inside otherwise mature architectures. In the next section, we present the design used to carry out our study. In Section 3, we report on the essential performances of the fabricated devices. In particular, investigations on the emission output power, spectrum, transmission characteristics are reported. A particular interest is brought to the study of the fabricated lasers performances depending on the nominal phase shift existing between the loss and index gratings, in order to discuss the advantages of combining gain and index coupling gratings. In Section 4, we investigate the asymmetric characteristics of the laser emission in a carefully designed setup probing optical transmission under electrical injection: these latter are strongly suggestive of the expression of a genuine PT-symmetry feature. In the last section (Section 5), we give data on the resistance to the impact of external optical feedback on coherence of lasers. We remind that the current cure to this lack of resistance and loss of coherence is the costly insertion of an optical isolator at the DFB output facet before the fiber, a large contributor to the cost and complexity of industrial laser modules.

2 Design and fabrication

Conventional DFB lasers used in optical networks nowadays separately exploit either gain-coupling or index-coupling mechanisms, respectively, involving a grating supporting a modulation of the material gain (loss) or of the material index of refraction, while complex-coupling ones involve both [4].

The main interest of applying the concept of PT-symmetry to DFB lasers is to take advantage of two features that improve the single frequency behavior through the simultaneous presence of index and loss modulation. One of these features is related to the gain discrimination mechanism of the lasing mode in the cavity with different types of Bragg gratings. Indeed, in the case of an index-modulated grating, the parameter that determines the advent and robustness of single-frequency operation is the difference in modal gain level between the pole with the lowest threshold and the next one. This difference is in turn related to the value of the index coupling coefficient [8]. Therefore, the discrimination among the different longitudinal lasing modes requires a grating with a large refractive index modulation.

The situation is different in the case of loss-modulated gratings. In this case, the laser effect occurs when a standing wave is formed in the cavity, whose field intensity distribution avoids loss regions and is mainly located in the loss-free regions (assuming a uniform background gain). As is evident from this picture, the minimum gain achievable for the threshold gain cannot be lower than that of a lossless Fabry–Perot cavity. For modes not resonating at all with the grating, the field is uniform, and the threshold gain level is that of a modified Fabry–Perot cavity, simply loaded with the average loss level inside it. This mechanism offers a much higher mode selectivity which explains the better single-frequency behavior of loss-coupled lasers, albeit at the expense of a larger threshold injection current.

In the case of complex-coupling, index-modulated and loss-modulated gratings are combined together. Figure 1(a) represents the principle of complex coupling with gratings made from physically separated contributions sensed by the waveguide mode, and the particular ridge waveguide implementation chosen in thus study. Adding the phase-shift degree of freedom, we are not only in the prolongation of the above-mentioned studies. Similar to them, we first exploit with this architecture the advantages of each constituent grating. The presence of the index-modulated grating ensures a lower threshold injection current, while the presence of losses improves the mode discrimination mechanism and makes single-frequency operation more robust. This feature has been noted in the past in a few publications on complex-coupled gratings [9–13].

More importantly, we are also attempting to exploit the interesting feature of the asymmetric coupling that can be obtained in gratings with elements of parity-time symmetry, meaning here obtained for the appropriate $\pi/2$ phase shift between loss modulation and index modulation, see Figure 1(a). Indeed, by implementing a PT-symmetrical Bragg grating in the laser cavity, the coupled contra-propagating waves should be affected by different effective coupling phenomena, one experiencing gain while the other undergoing loss. This characteristic may be of great interest for the operation of the DFB because the coupling of external reflections from the main output side, which are harmful to the laser operation, could be attenuated inside the cavity, and in particular the commonly resulting loss of coherence could be avoided.

To validate these hypotheses, DFB lasers with different types of index profiles were experimentally fabricated, as shown in Figure 2. The fabrication process included index, gain and complex-coupled (CC) DFB lasers integrated in a common process consisting in the structuring of a two-quantum-wells structure into InP/InGaAsP. The basic design structure requires transverse single mode behavior, that is achieved following modeling of the ridge waveguide dimensions. A typical width of 2 µm is adopted together with a height of about 1.5 µm, corresponding to the thickness of the p-InP capping layer. Etching is then carried out down to the InGaAsP separate confinement heterostructure (SCH). Corresponding optical confinement factors are in the range adapted to the laser cavity length. Typical distance between metal and dielectric grating is dictated by fabrication tolerances and is on the order of 50 nm. The metal grating stripe width is equal to a half period $\Lambda/2$ = 360 nm (see also Figure S3 in Supplementary Material). The particular flavor of DFB laser ridge, whose structure is shown in Figure 1(b), has a taller exposed ridge than other technologies, e.g., the more popular buried ridge stripe (BRS) type, but this choice is also represented in commercial devices [14]. Since the active layer is not etched, it actually belongs to the shallow ridge category, which does not compromise lasing performances versus BRS and has the advantage of allowing efficient interaction of the propagating mode with the nanosized features of interest of the grating. This provided

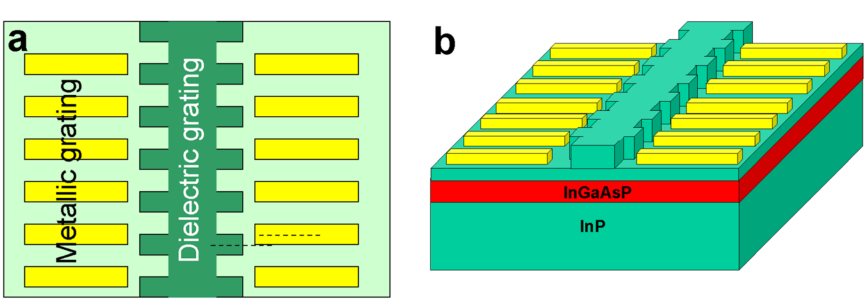

Figure 1: a) Principle of parity-time (PT) symmetric gratings, with symmetry planes of gratings (dashed lines) shifted by a quarter period; b) Implementation using a dedicated waveguide ridge technology. The parity (P) operator corresponds to the dielectric grating symmetry plane (lower dashed line) while the time (T) operator flips the sign of Im(n) modulation versus its nonzero mean value.

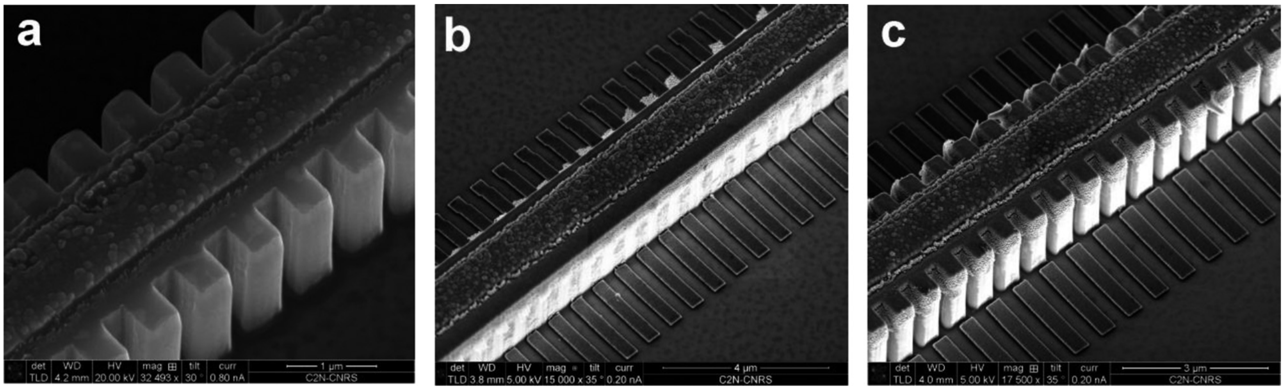

Figure 2: SEM pictures of fabricated Distributed Feedback laser diodes (DFB) lasers.
a) Index-coupled (IC) DFB with third-order dielectric grating; b) gain-coupled (GC) DFB with third-order metallic grating; c) third-order complex-coupled (CC) DFB. Bragg grating periods amount to about 750 nm.

us here in particular with the characteristics of the index and gain gratings, both of which are found in the cavities of the CC DFBs. The real part of the modulation of the index is provided by the variation of the width of the laser ridge waveguide. The effective index is computed using a mode solver and the modulation of the imaginary part of the index is provided by a metal grating. From experimental data of transmission and reflection measurements, we determined that for such CC grating the modulation Re(Δn) is about 1.2×10^{-3} and Im(Δn) is about 2×10^{-4}. To define the index grating, a highly anisotropic etching process was developed using inductively coupled plasma (ICP) reactive ion etching (Figure 2a). This only involves standard methods commonly used in the fabrication of contemporary photonic integrated circuits. To avoid any bias due to possible misalignments, the emission characteristics were studied within groups of neighboring lasers on the same cleaved bar. The laser physical length is typically slightly below 1 mm, setting a cavity free spectral range of ~0.4 nm between the facets.

The index-coupled (IC) structure bearing a laterally corrugated grating is operated at third Bragg order. The gain-coupled (GC) grating was implemented through the deposition of lateral metallic stripes (Figure 2b) by a lift-off technique. Two different gratings operated in a first order as well as in the third order were fabricated. The double-grating CC DFB structure comprises a third-order dielectric grating and a third-order metallic grating (Figure 2c). The choice of the third order for the grating was motivated by the readily available technology process at our laboratory. Parity-time symmetry condition is still fulfilled with this grating order. In order to highlight the asymmetrical behavior related to the PT-symmetry, eight types of gratings with relative phase between dielectric and metal grating ranging from 0 to 7Λ/8 with a phase step of Λ/8 were fabricated according to the scheme of Figure 1a.

3 Experimental results and analysis

The light–current (LI) characteristics were measured using a photodiode and an automatized pulsed current generator with low duty cycle to avoid heat-sinking biases, e.g., between bar edge and bar center. A typical LI characteristic of our CC DFB laser is presented in Figure 3a, the lasing threshold is situated around 40 mA with an output power at 200 mA around 16 mW per (cleaved) facet. The optical spectrum was measured using a high-resolution Optical Spectrum Analyzer (OSA). The emission spectra measured on such third-order CC DFB lasers are monomode, with a Side Mode Suppression Ratio (SMSR) over 50 dB (see Figure 3b).

In stark contrast, third-order IC DFB lasers operated under the same injection current of 120 mA presented multimode spectral behavior (see Figure 4a), while the third-order metallic grating GC DFB lasers did barely reach their lasing threshold (see Figure 4b). These results are fully consistent with theoretical expectations and thus prove the interest of combining together index-modulated and loss-modulated gratings. Furthermore, the comparison between third-order complex-coupled and conventional first-order metallic grating DFB lasers (Figure 4c) revealed that the association of metallic and dielectric gratings leads to similar performances in terms of emission power and enhanced monomode operation. This opens the opportunity to relax grating fabrication to third-order rather than first order so as to mitigate fabrication constraints while keeping acceptable performances.

It should be noted that among CC gratings with eight values of relative phase shifts, PT-symmetric configurations predominantly showed better performances. As practitioners know, high-efficiency lasers result from a delicate trade-off as

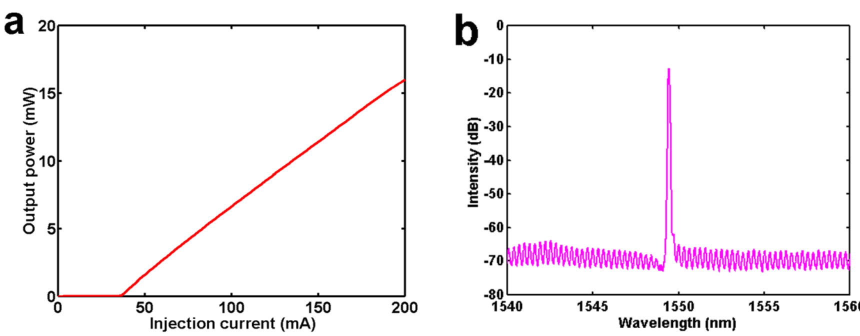

Figure 3: Performance of third-order complex-coupled (CC) DFB laser.
a) Light-current (LI) characteristic, showing the evolution of the emission output as a function of the injection current; b) Emission spectrum taken at a current of 120 mA.

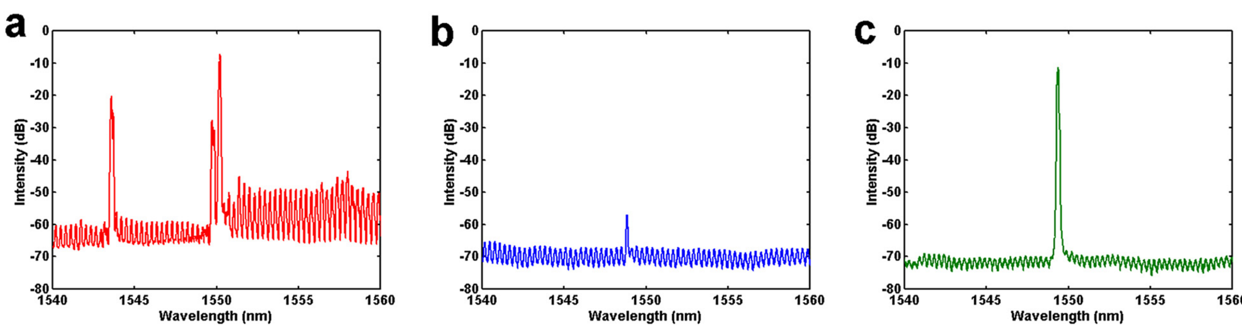

Figure 4: Emission spectra at 120 mA of a) index-coupled (IC) Distributed Feedback laser diodes (DFB) laser with third-order dielectric grating; b) gain-coupled (GC) DFB laser with third-order metallic grating; c) GC DFB laser with first-order metallic grating.

the grating strength should be limited; hence, the presence of minor extra mode selection mechanism is often an issue in such studies, and is hard to entirely circumvent.

4 Transmission probing experiments

Here, as indicated above, we assert that the origin of the better performance may be related to the asymmetric light transport caused by unidirectional reflection [15, 16]. To verify this assumption, we performed additional experiments by externally probing our lasers with a tunable laser, and acquiring the transmitted and reflected spectral response using the experimental setup shown in Figure 5. The principle is the injection of an incident wave generated by an external tunable laser (Tunics from Yenista), into the laser cavity (possibly injected with current as well to operate around a resonant regime without absorption of the active layer) and the probing of reflected and transmitted waves. Care was taken to remain in a linear regime using relatively low probing optical power. The transmitted signal is collected by a microscope objective focusing the light from the output facet to a multimode fiber. The reflected signal, on the other hand, is instead collected by the same monomode lensed fiber with 2 μm focusing waist from OZ Optics used to inject light inside the cavity, from which one half is separated by a 50/50 coupler. The input beam polarization is controlled by a fibered polarizer at the entrance of the setup, and by a second polarizer at the output end of the laser. A broadband detector (Model CT400 from Yenista) records data coming from transmission and reflection arms, and compares them to the reference incident beam.

As noted above, the manifestations of PT-symmetry beyond exceptional point include unidirectional behavior in the light propagation. In particular, for the case of parity-time symmetric Bragg reflector such as our lasers, theoretical works clearly pointed out that periodic gain or loss should affect the reflected light in one direction of the grating only. This characteristic can possibly improve the resistance of lasers integrating parity-time symmetric (PTS) Bragg gratings to external optical feedback, the underlying principle being that the feedback light is prevented to interfere with the whole modal field across the entire cavity.

As the setup described above is able to probe reflection and transmission spectral characteristics of our lasers for a wide range of parameters, PT-symmetric behavior should, in principle, be observable from the data we acquired. Figure 6 is a comparison of reflected (red) and transmitted (blue) waves amplitude in opposite directions of the device (left and right figures). In this example shown in Figure 6c and d, for 1.5 mm cavity length laser and 60 mA injection

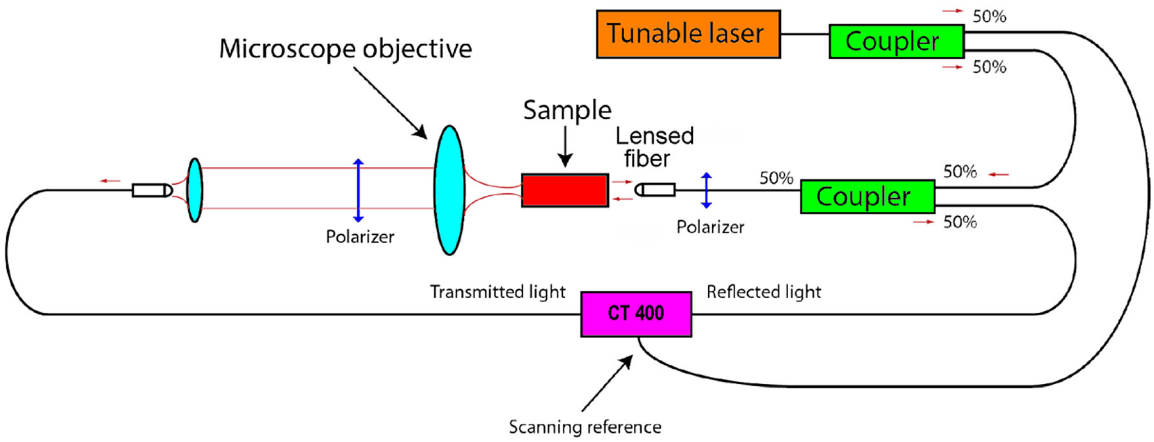

Figure 5: Presentation of the setup used to measure the transmission and reflection characteristics of our lasers.

current, we observe that a mode is amplified by ~6 dB in reflection in one direction (left spectrum) while in the opposite direction (right spectrum) the reflection remains nearly constant. Note that the transmission should be identical in both directions due to Lorentz reciprocity [17] and the measurement clearly confirms this principle. The effect of unidirectional amplification in reflection is observable only in a very narrow range of injection currents near the lasing threshold. Thus at a lower injection current of 50 mA, this effect is only barely visible (Figure 6a and b).

5 Resistance to optical feedback

As a crucial test towards real-world applications of these lasers, the resistance of Complex-Coupled DFB lasers to external optical feedback was investigated under the same protocol as conventional DFB lasers of the IC type. The quantity probed is the so-called optical return loss (ORL), the smallest optical return loss that compromises the coherence, as probed by adequate spectroscopic means in the form of spectral broadening, the so-called laser coherence collapse denoted hereafter LCC. We are here interested in observing the added value of both gain and index coupling combination to the resistance to external feedback, and potential asymmetry in this resistance depending on the gratings relative phase. Indeed, such behavior could be the manifestation of PT-symmetric behavior of the grating action, resulting from the difference in coupling between forward-to-backward and backward-to-forward waves. Relatively high tolerance to optical feedback is usually achieved by the use of an active medium which ensures high differential gain and low linewidth enhancement factors [18, and references herein]. In order to highlight the effect of PTS waveguides on the optical feedback, we purposefully adopted a structure with relatively low optical confinement and differential gain. This consists of a 2-quantum well (QW) active layer embedded in a GaInAsP separate confinement heterostructure (SCH), grown by Gas Source Molecular Beam Epitaxy (GSMBE).

In a recent theoretical study, Ke et al. evaluated the effects of external optical feedback on a PT-symmetric DFB laser from the induced change in lasing wavelength, reduction in SMSR and eye-diagram performances [19]. From the comparison with conventional IC, GC and phase shifted IC DFB lasers, this modeling work showed that PTS DFB lasers present improved operation under external optical feedback, judging by the three aforementioned criteria. One reason argued to explain this improved resistance is that the asymmetry brought by the shift between real and imaginary parts of index induces a weaker reflection, expected to have less impact on the steady-state lasing condition.

Optical feedback experiments were performed for the three types of DFBs and a rather large dispersion of the results was found, depending on laser type and cavity length. This was the case for the CC devices for which the onset of coherence collapse varied from about −35 dB for the less robust ones, to high enough levels complying with the isolator free IEEE 802.3 standard at over −21 dB.

To test the hypothesis of feedback resistance due to the expression of PT-symmetry, the lasers were tested with external reflection along both directions. The typical asymmetry of GC DFB lasers is a few dB and was likely affected by the facets to a substantial amount, making a study as a function of grating phase on this performance delicate in our chosen GC regime. Such an asymmetry is also common in our pure CC and IC DFB lasers, indeed. However, the observation of one laser with a remarkably high asymmetry ~10 dB) within a modest batch of a few lasers on a bar is of good omen for the possibly increased performance of PTS lasers.

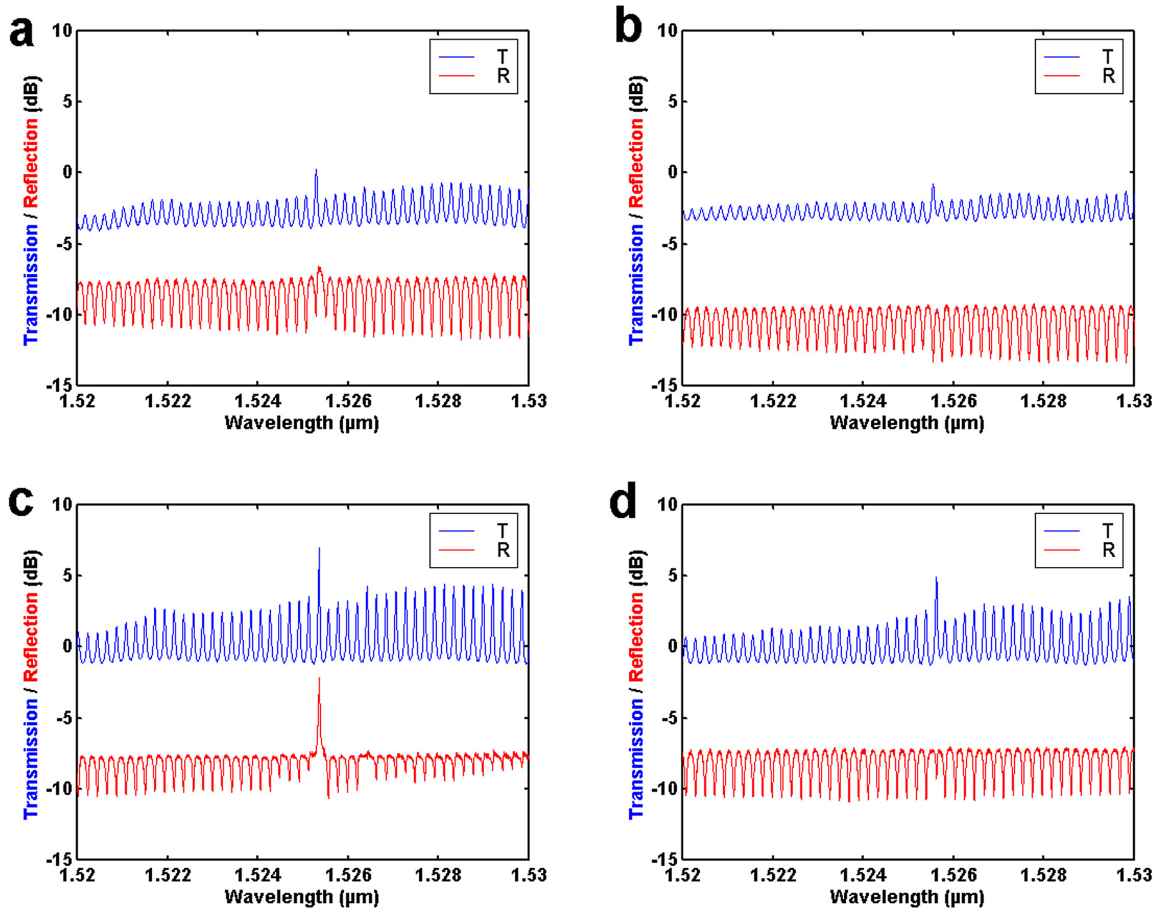

Figure 6: Example of transmission (blue) and reflection (red) spectra showing asymmetric amplification. On one direction (left-hand figures), the reflection is amplified at a Bragg wavelength, while the reflection spectrum in the opposite direction (right-hand figures) is not. a) and b) Injection current $I = 50$ mA; c) and d) Injection current $I = 60$ mA. The reflection spectra are offset for clarity by −10 dB with respect to transmission one.

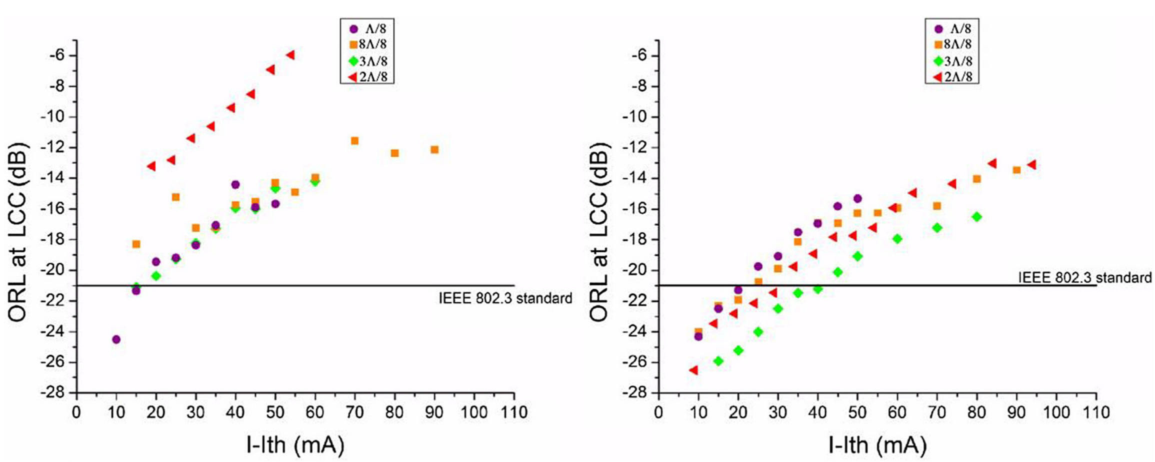

Figure 7: Direction-dependent resistance to external feedback of complex-coupled (CC) Distributed Feedback laser diodes (DFB) lasers cleaved from the same 1980 µm length bar and with differing grating phase shifts as function of the difference between the injection current I and the threshold current I_th. Sample 2Λ/8 corresponds to a quarter period phase shift between the gain and loss gratings. The left graph is for probing from one side of the chip, the right graph is from the other side.

This is shown in Figure 7 for a cavity length of about 2 mm and varying nominal phase shifts between index and metal grating. The largest difference is observed for a nominal quarter period phase shift and amounts to about 10 dB (sample 2Λ/8), with more modest differences for the other phase shifts. Smaller differences (~5 dB) are observed for a shorter laser cavity (1.3 mm).

6 Summary and conclusions

We have investigated the first implementation to our knowledge of DFB laser diodes that combine the capability of real-life telecom-grade performances with the advanced concept of PT-symmetry, involving both dielectric and gain modulation with a well-defined phase relation of the corresponding gratings (ideal quadrature in the case of PT-symmetry). We developed a specific ridge waveguide technology, with deep corrugations for the dielectric lattice and metal stripes for the gain/loss modulation. The laser performances in terms of single-frequency behavior are at the state-of-the art, with routinely achieved >50 dB SMSRs and output powers exceeding 14 mW. We also investigated their nonreciprocal reflexion behavior in a dedicated setup showing clear signatures of directional amplification. Finally, in a first attempt to take advantage of non-reciprocity effects to increase optical feedback robustness, we report preliminary encouraging data showing strong asymmetry in the feedback resistance.

The study was carried out using third-order dielectric and absorption gratings. The achievement of some performances comparable to first-order grating devices (e.g., spectral purity) is a good sign of the potential of the approach. Modifications of various key parameters such as coupling coefficients and the grating order should be further investigated to fruit the full potential of this novel approach.

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