Dispersive Self-$Q$-Switching in Self-Pulsating DFB Lasers

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Abstract—Self-pulsations reproducibly achieved in newly developed lasers with two distributed feedback sections and with an additional phase-tuning section are investigated. The existence of the dispersive self-$Q$-switching mechanism for generating the high-frequency self-pulsations is verified experimentally for the first time. This effect is clearly distinguished from other possible self-pulsation mechanisms by detecting the single-mode type of the self-pulsation and the operation of one section near the transparency current density using it as a reflector with dispersive feedback. The operating conditions for generating this self-pulsation type are analyzed. It is revealed that the required critical detuning of the Bragg wavelengths of the two DFB sections is achieved by a combination of electronic wavelength tuning and current-induced heating. The previous reproducibility problems of self-pulsations in two-section DFB lasers operated at, in principle, suited current conditions are discussed, and the essential role of an electrical phase-control section for achieving reproducible device properties is pointed out. Furthermore, it is demonstrated that phase tuning can be used for extending the self-pulsation regime and for optimizing the frequency stability of the self-pulsation. Improved performance of the devices applied as optical clocks thus can be expected.

Index Terms—DFB laser, dispersive reflector, multisection laser, optical pulse generation, $Q$-switching, self-pulsation.

I. INTRODUCTION

SELF-PULSATIONS in two-section distributed feedback (DFB) lasers were discovered in 1992 [1]. The self-pulsating DFB lasers exhibit some very attractive features. Much higher frequencies [2], [3] than by absorptive self-pulsations can be achieved (80 GHz have been demonstrated). The frequency can be tuned electrically and continuously over a wide range, and the self-pulsations can be locked to an optically injected data stream [4]. High-frequency all-optically synchronized pulse sources can thus be established.

In [1], it was pointed out that the observed self-pulsations were different from those of the well-known absorptive type and a new dispersive type of self-pulsation in DFB lasers was proposed. Follow-up model calculations revealed that at least three different mechanisms could be responsible for explaining DFB-type self-pulsations. These are:

- dispersive self-$Q$-switching [5], [6];
- spatial hole burning [6]–[8];
- beating type oscillations [9].

Further experimental investigations in different laboratories showed quite a variety of results regarding the conditions for generating the DFB-type self-pulsations and regarding the achieved device properties. Self-pulsations at frequencies below 5 GHz were found in a few laboratories, e.g., 300 MHz [7], 2.5 GHz [8], and 4 GHz [10], while self-pulsations at frequencies in the 10–100-GHz range were reported so far only from the Heinrich–Hertz-Institute [2]–[4]. Investigating many of our two-section DFB lasers, we obtained self-pulsations in every device. But lasers showing self-pulsations above 10 GHz had to be selected.

For applications in high-speed signal processing, the high-frequency self-pulsations are particularly interesting. However, without a reproducible fabrication procedure, a definite clarification of the effective mechanism and a clear description of the required operating conditions, such devices are of no practical use. Recently, we achieved reproducible high-frequency self-pulsations in lasers with two DFB sections and an additional phase-tuning section [11]. The purpose of this paper is to identify the mechanism which is responsible for generating the self-pulsations in this new device type, to analyze the operation conditions for the self-pulsations and their physical background, and to make clear the essential function of the electrical phase-tuning section for controlling and optimizing the self-pulsation.

In Section II, the device design and current conditions for obtaining reproducible high-frequency self-pulsations are presented. In Section III, the three different mechanisms proposed so far for explaining DFB-type self-pulsations are discussed and their characteristic features are pointed out. The type of the presently investigated self-pulsation is investigated in Section IV. The function of one DFB section as a dispersive reflector is analyzed, optical spectra in the self-pulsating operation are measured, and the corresponding results are compared with the proposed characteristics of the distinct effects discussed in Section III. Dispersive self-$Q$-switching thus is identified as the responsible mechanism. Section V investigates the critical spectral correlation which is required for achieving dispersive self-$Q$-switching. The detuning of the Bragg wavelengths of the two DFB sections by electronic effects and by current-induced heating is measured for this purpose. At last, in Section VI, the decisive function of the...
electrical phase-control section for reproducible generation of the self-pulsation and for optimization of the self-pulsation is described.

II. REPRODUCIBLE GENERATION OF HIGH-FREQUENCY SELF-PULSATIONS

A. Device Development

High-speed self-pulsations so far were only obtained by our group and only in DFB lasers with at least one uncoated facet. One reason for the missing reproducibility even between devices cleaved from the same laser bar can be the variation of the phase of the facet reflectivity. AR-coating of two-section DFB lasers was performed, but the high-frequency self-pulsations were not obtained by this procedure. We concluded that possibly not the suppression of the facet reflectivity is the solution, but that very special phase conditions of the facet reflection must be adjusted for generating the self-pulsations. Unfortunately, a technological precise adjustment of the facet position relative to the DFB grating with an accuracy on the 10-nm scale cannot be achieved, neither by cleaving nor by etching of the facets.

As an alternative to the problematic technological adjustment of the critical parameter, it is much more feasible to implement an electronic tunability of the phase conditions in the device. For realizing this function, the device shown in Fig. 1 was developed. The device consists of two DFB sections and an additional phase-tuning section. The facet at the phase section was not AR coated. Details on the device fabrication are given in [11]. The two DFB sections in the device can be operated like the (selected) two-section DFB lasers which exhibited single mode high frequency self-pulsation previously [1], [4]. In addition, the phase of the facet reflection can now be tuned by current injection into the phase section. Instead of phase conditions in cleaved two-section DFB lasers which vary randomly from device to device, one now can adjust any desired phase condition of the light reflected from the facet. In [11], it is proved that the generation of self-pulsations really depends on the phase conditions. Self-pulsations can be turned on and off using the phase current as an electrical switch. This switching function works in all devices cleaved from the same laser bar. Reproducible fabrication and operation of self-pulsating devices thus is possible.

B. Current Regime for Self-Pulsation

The current conditions in the DFB sections which are required for generating the self-pulsations are of special interest. They are investigated in the following.

In [11], it was shown that the self-pulsations can be switched on and off periodically by increasing the phase current. The frequencies decrease from period to period. In the following investigations, the phase current was fixed to 57 mA. This current corresponds to the sixth period and a pulsation frequency of about 10 GHz. The center section, called the laser section in the following, is operated high at 133 mA. The current in the DFB section at the AR-coated facet (called the reflector section) is increased and the measured RF spectra are shown in Fig. 2. At 2.7 mA, a self-pulsation at 8 GHz can be observed. Increasing the reflector current to 5 and 8 mA, the frequency increases to 9.5 and 10.5 GHz, respectively. The second harmonic is strong at 8 GHz and decreases with increasing frequency. Below 2.6 mA and above 8.5 mA, the device emits continuously.
about single-mode self-pulsations in two-section DFB lasers. One can assume that the same self-pulsation type is effective in all these devices. Self-pulsations at very asymmetric current conditions previously have been assigned to dispersive self-Q-switching. But being confronted with three mechanisms proposed so far for explaining DFB-type self-pulsations and with a puzzling variety of published experimental results, a definite verification of the dispersive self-Q-switching effect was not possible yet. The reproducible self-pulsation properties achieved with the new device type are now a good basis to reveal the typical features of the underlying effect and to identify the type of the self-pulsation. Toward this, the three different mechanisms proposed so far in literature for explaining DFB-type self-pulsations are shortly described in the following section and their different characteristics are pointed out. This knowledge is required for distinguishing then the different effects and for identifying the type of the presently investigated self-pulsations.

III. PROPOSED MECHANISMS FOR DFB-TYPE SELF-PULSATIONS

A. Dispersive Self-Q-Switching

The dispersive feedback of a DFB section can be illustrated by the amplitude reflectivity. Its spectrum is shown in Fig. 4 for the case that the section is operated at the transparency current density. Important for self-pulsations is the existence of the steep slopes in the reflectivity spectrum, which are visible near the reflection minima. In a two-section DFB laser, one section can be operated as a reflector with the described features, and the second one can be operated well above the lasing threshold. The decisive condition for achieving the self-pulsations is that the lasing wavelength from the highly pumped laser section coincides with a steep slope in the reflectivity of the low pumped reflector section. At this operating point, the threshold of the lasing mode shows a strong dependency on wavelength, because the threshold conditions are directly correlated with the reflectivity of the resonator at this wavelength. It is well known that any amplitude modulation is correlated with a wavelength modulation via the alpha factor. Therefore, at the operation point discussed above, the threshold conditions are varied during an amplitude modulation. As a consequence, the laser switches itself off after emitting a short optical pulse and turns on again after a recovery time. The basic effect is the variation of the reflectivity, which modifies the relation of the optical power in the laser cavity to the optical power emitted from the laser facets. This relation is called the Q-factor of a resonator. As this Q-factor is varied by dispersive effects and without any external modulation, one can describe the basic effect for this type of self-pulsation as a “dispersive self-Q-switching.”

Bandelow et al. [5] used a single-mode model based on the traveling wave equations for analyzing this type of self-pulsation. Recently, Marcenac et al. [6] applied a time-domain model to lasers of similar structure. They also identified single-mode self-pulsations of the type described above, confirming the results from Bandelow, and predicting frequencies above 10 GHz. Important features of this DFB type self-pulsations are:

- single-mode nature of the self-pulsations;
- strong asymmetric pumping of the two sections;
- high frequencies >10 GHz can be achieved.

B. Spatial Hole Burning

The second mechanism proposed relies on spatial hole burning. If, during the rising of an optical pulse, the gain of the respective lasing mode is reduced by spatial hole burning, then hopping to another laser mode will occur. Lasing will jump back to the first mode after a gain recovery time, and by periodic repetition of this process, self-pulsation can occur. Marcenac et al. [6] theoretically found the possibility of periodic hopping of the lasing action between the two modes on the long and short wavelength side of the stop band. Spatial hole burning was the mechanism leading to this type of self-pulsations. Using a transmission line model, Lowery et al. [8] attributed observed self-pulsations to a mode hopping between an unstable asymmetric and a stable symmetric mode with higher threshold. Again, spatial hole burning is involved in the switching process. Phelan et al. [7] assume that spatial hole burning in addition to dynamic interchange of carriers between the sections is responsible for self-pulsations in multisection DFB lasers. Common to all these published models are: 1) multimode emission in the self-pulsating state, and 2) only moderate frequencies (less than 5 GHz) are expected.
C. Beating Type Oscillations

The third mechanism for self-pulsations in two-section DFB lasers has been proposed by Wenzel et al. [9]. It relies on beating between two DFB modes. If both DFB sections are operated at sufficiently high currents, then each section can generate its own DFB lasing mode. Two modes of different wavelengths will cause an amplitude modulation of the emission due to the beating effect, with a frequency corresponding to the wavelength difference. Important is the coupling of photons from one section with the carrier density in the other one, which distinguishes this type of self-pulsations from simple interference of two waves. Characteristic features of beating type self-pulsations are:

- basically a multimode emission;
- highly pumping of both DFB sections;
- frequencies up to 100 GHz are possible.

IV. VERIFYING DISPERSIVE SELF-$Q$-SWITCHING

From the description above, it turns out that two features are especially suited for distinguishing dispersive self-$Q$-switching from the other mechanisms. First, it is the only self-pulsation which can work in single mode, and second, one DFB section is operated close to its transparency and acts mainly as a passive wavelength-dependent reflector.

A. Investigations on the Reflector Section

A DFB section shows a reflectivity spectrum as sketched in Fig. 4 if it is operated at the transparency current density. The first target is therefore to analyze the transparency current density of the used laser heterostructure and to compare this value with the current conditions required for generating the self-pulsation and shown in Fig. 3.

The gain–current characteristic of the laser heterostructure was measured applying the method of Hakki and Paoli [12] on Fabry–Perot lasers processed parallel to the DFB lasers on the same chip. Results are shown in Fig. 5. The measured parameter is the net gain, and zero gain therefore corresponds to the waveguide transparency. This value is achieved at a current of 13 mA. Self-pulsations as shown in Fig. 3 were achieved for currents between 2.7 and 8 mA. The self-pulsation regime on the current and on the gain scale is indicated as a dark stripe in Fig. 5. Obviously, the reflector section has a negative net gain within the self-pulsation regime.

The transparency of the active layer was investigated also. For this purpose, a strong light signal was injected into the laser structure and the optically induced voltage change at different currents was measured. The optically induced voltage modulation changes its sign just at the gain transparency current of the active layer. Using this method, a transparency current of 7.3 mA at a wavelength of 1570 nm was determined, which corresponds to a net gain of about $-25$ cm. Comparing this value in Fig. 5 with the self-pulsation regime, it turns out that the reflector section is operated near the gain transparency of the active layer. As a consequence, the carriers of this section do not couple to the optical power and, hence, can play no role for the dynamics of the self-pulsations. This is in full accordance with the analysis given in [5].

In summary, it can be stated that in the self-pulsation regime analyzed here the reflector section has no significant absorption or gain. The essential function of the reflector section is the optical feedback with its strong dispersive characteristic.

B. Analysis of Optical Spectra

The second indicator for verifying dispersive self-$Q$-switching is to check the single-mode nature of the self-pulsation. Fig. 6 shows emission spectra from the device in stable and in self-pulsating operation. In stable operation [Fig. 6(a)], the emission is single mode at 1572 nm with a side-mode suppression (SMS) of better then 50 dB. It can be seen that lasing is correlated with the mode on the long wavelength side of the stop band. By increasing the reflector current, the device is switched to self-pulsation at 8 GHz. The corresponding emission spectrum is shown in Fig. 6(b). Lasing still occurs single mode at 1572 nm, with a SMS (peak to peak) of better than 35 dB. The reduction in the SMS and the broadening of the emission line are both caused by the splitting of the emission line into side bands, according to the self-modulation. The investigations verify that the self-pulsation is of single-mode type and not correlated with mode hopping caused by spatial hole burning.

Optical spectra can also be used to distinguish dispersive self-$Q$-switching from beating type oscillations. In beating type oscillations, two main modes plus side bands must exist. In dispersive self-$Q$-switching, an amplitude modulation of a single line occurs, and thus one can expect one central mode plus side bands. In Fig. 7, the existence of a central mode can be clearly recognized in the spectrum according to 8 mA. The self-pulsation is clearly identified as single mode. But, it should be noticed that the analysis is simple only in the case of a relatively pure amplitude modulation. If amplitude and phase modulation are simultaneously present, the central mode can be weaker than the side bands (for phase modulation the amplitude of the central mode is described by a Bessel function of zero order and can become, for example, zero for special modulation indexes). This is visible in the spectra at 6 and 4 mA. Also, if the amplitude modulation is
accompanied by a frequency modulation, then the amplitudes of the side bands become asymmetric. One side band can grow up to an amplitude similar to that of the central mode, and thus the spectra can look to be a beating type. The spectrum in [11] indicating 30 GHz self-pulsation is an example for asymmetric side bands. As a consequence of the sometimes ambiguous spectra, one has to investigate not a single spectrum but series of spectra in order to get a clear answer regarding the mechanism causing the self-pulsation. Using this method for the presently investigated self-pulsation, the existence of a central mode could be clearly identified. Dispersive self-switching as the responsible mechanism is also confirmed by the current conditions for generating the self-pulsations. Beat type oscillations require a high pumping of both DFB sections, and this is obviously not the case here.

All the presented experimental results coincide very well with the model of dispersive self-Q-switching: the asymmetric pumping conditions, the operation of one section at the transparency current density as a reflector with dispersive feedback, the single-mode type of the self-pulsation, and the high frequencies achieved. The two other discussed mechanisms can be excluded. Thus, for the first time, the existence of dispersive self-Q-switching has been verified experimentally.

V. Adjusting the Spectral Correlation Laser Reflector

One precondition for self-pulsations to occur is the existence of a reflection characteristic in one section with a steep spectral slope. A second requirement is the coincidence of the lasing wavelength with this spectral range with a steep slope. This spectral correlation can be adjusted by the detuning of the Bragg wavelengths in the two sections caused by the strongly different current injection levels. Two contributions must be considered: electronic effects due to the increase of the carrier density, which will lead to a blue shift of the Bragg wavelength, and current-induced heating causing a red shift. The electronic and the thermal contributions to the index of refraction must be analyzed in order to describe the detuning of the Bragg wavelength in the two sections correctly.

A. Investigations on Current-Induced Electronic and Thermal Wavelength Shifts

Current-induced variations of the index of refraction can be investigated straightforwardly by measuring the current-induced shift of the mode comb in a FP laser. Therefore, a FP laser processed on the same chip as the DFB laser and with the identical heterostructure was used for the investigations. Results are shown in Fig. 8. The wavelength shift is plotted as a function of the current length. Below threshold, the carrier density increases with current injection. A resulting electronic blue shift of \(2.1 \text{ nm/mA} \times \text{m}^2 \) with the current normalized to the section length has been found [Fig. 8(a)]. Above threshold, the carrier density is nearly fixed. There, the dominant effect is current-induced heating, which generates a
red shift. From the measurements shown in Fig. 8(b), a thermal wavelength shift of 0.57 nm/mA/μm can be derived.

B. Current-Induced Detuning of the Bragg Wavelengths

The values determined above can be transferred to the DFB laser in order to analyze the detuning of the Bragg wavelengths of the two DFB sections at different operating points with and without self-pulsations (Fig. 9). From an equal current density in both sections (e.g., 8 mA in reflector and laser) up to the lasing threshold (about 38 mA in the laser section), the electronic effect will cause a blue shift of about 3 nm. At threshold, therefore, the long-wavelength DFB mode of the laser section will be the dominant one, because this mode is spectrally correlated with the high reflectivity within the stop band of the reflector section. Increasing the laser current above threshold, the thermal effects will cause a red shift of the Bragg and lasing wavelengths. At sufficiently high currents, the lasing mode can be tuned thermally to the steep slope of the reflectivity on the long-wavelength side of the reflector stop band. At such an operation point, self-pulsations will occur (Fig. 4).

In the experiment described in Section II, self-pulsations were achieved between about 130 and 140 mA. The red shift from threshold to the self-pulsation regime is about 2.8 nm. Comparing electronic blue and thermal red shift, it turns out that at the self-pulsation conditions both approximately compensate for each other. Surprisingly, the laser and the reflector section are not significantly detuned regarding their Bragg wavelength, though the pump currents are extremely different. It turns out that the lasing first long-wavelength DFB mode is correlated spectrally with the steep slope in the reflectivity on the long-wavelength side of the stop band of the reflector section.

It is an important result of our analysis that at the operating condition for self-pulsations such a characteristic spectral correlation between the lasing wavelength and a steep slope in the spectral feedback of the reflector is present in agreement with the model. However, the mode correlations observed in the investigated device are quite different to those assumed in the published models [5], [6], which only consider electronic detuning of the Bragg wavelength.

VI. FUNCTION OF THE PHASE-TUNING SECTION

Even knowing the current requirements for generating the self-pulsations it was observed experimentally that only a small number of two-section DFB lasers exhibited this type of self-pulsation. An additional phase-tuning section was required for reproducibly generating self-pulsations.

A. Mode Selection

For achieving self-pulsations, it is indispensable that this DFB mode, which is tuned to the required correlation with the steep slope in the feedback spectrum of the reflector section, is also the dominant mode which carries the lasing process. In a DFB laser, many optical modes exist, and the mode of lowest threshold gain will be the dominant one. Obviously, a lasing mode tuned to the wavelength suited for self-pulsation experiences a low reflectivity of the reflector section and thus has an increased threshold gain.
One can recognize this effect, e.g., in Fig. 6. An increased threshold gain of the dominant mode causes an increase of the carrier density and as consequence also of the gain of the side modes. Switching the lasing mode by the phase current from stable to self-pulsation operation, one can observe in Fig. 6 an increase of about 10 dB in peak power of the short-wavelength DFB mode. As the DFB currents are fixed, this indicates that the threshold gain of the dominant mode is higher in the self-pulsation regime than in continuous operation.

Instead of self-pulsating operation, hopping to another mode with lower threshold gain and with continuous emission can be the consequence. Especially at the required high operating currents, this effect is very probable. An additional parameter is required to prevent this mode hopping and to force the lasing mode to the critical spectral correlation. In the considerations up to this point and in the amplitude reflectivity shown in Fig. 4, the phase round-trip conditions, which must be fulfilled, had not been regarded. However, tuning of the phase conditions can lead to the required mode selection and tuning. In as-cleaved two-section DFB lasers, the mode fulfilling the self-pulsation conditions was supported and selected for lasing by randomly occurring phase conditions. In the developed three-section device, the suited phase conditions for lasing in the self-pulsating mode can be adjusted electrically and the self-pulsation can be switched on and off electrically.

B. Optimization of the Self-Pulsation

Compared with fixed phase conditions, the electrical tunability of this parameter has additional advantages. First, if the self-pulsation frequency is tuned by varying the laser current, then the unavoidable thermal wavelength tuning will shift the lasing mode away from the ideal operating point. In [11], it has been shown that the phase tuning has an effect not only on selecting a mode for lasing, but also on tuning the wavelength. The detuning from the optimum spectral correlation can thus be compensated partly by readjusting the phase conditions properly. As a consequence, one can achieve an extended current regime for self-pulsations. This is demonstrated in Fig. 10, where the self-pulsation regimes at fixed and readjusted phase conditions are compared. The extended regime is clearly visible.

A second advantage of adjusting optimum spectral correlations by the phase tuning regards the frequency stability. In

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**Fig. 10.** Extended self-pulsation regime regarding the DFB currents achieved by readjusting the phase conditions.

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**Fig. 11.** Optimization of the RF linewidth by phase tuning. Laser/reflect current: Fixed to 125 mA/8 mA.

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**VII. CONCLUSION AND OUTLOOK**

It has been experimentally verified for the first time that the high-frequency (10-GHz range) self-pulsations achieved reproducibly in DFB lasers with a phase-tuning section are caused by the mechanism of dispersive self-$Q$-switching. The current regime for self-pulsations is analyzed and it is clearly shown that one section is operated near the transparency current density, using it as a reflector with dispersive feedback. Electronic as well as current-induced thermal wavelength tuning effects were investigated. The importance of both effects on the detuning of the Bragg wavelengths in the two sections and on achieving the spectral correlation required for generation of the self-pulsations has been revealed. The decisive function of the phase-tuning section was pointed up. The phase-tuning facility is essential for reproducible fabrication of self-pulsating devices. In addition, extended self-pulsation regimes can be achieved, and the frequency stability can be improved.

All together, the mechanism of dispersive self-$Q$-switching has been verified and an overview on the features of the corresponding self-pulsations has been given. However, the self-pulsations in multisection DFB lasers are still complex effects. Investigations and applications therefore should take into account the following points. First, self-pulsations of the different types discussed previously can perhaps be obtained even in one device, at different current conditions. Secondly,
as a consequence of the many laser modes present in DFB lasers, more than one spectral correlation could be suited for generating self-pulsations. A very simple case is the thermal tuning of the lasing wavelength to the second long-wavelength reflectivity minimum. In a generalized view, any correlation of a lasing DFB mode with a negative slope in the spectral reflectivity can result in self-pulsations by dispersive self-$Q$-switching. More than one current regime for self-pulsations therefore can exist, as, for example, can be observed in [1]. Third, in the discussion, we treated the sections as separate ones, a laser and a reflector section. This is very helpful to understand and discuss the basic effect. But for quantitative analysis, a more complex modeling of the laser modes, their spectral correlations including thermal effects, and the reflectivity feedback is required. The results of modeling of the whole three-section laser based on the coupled mode theory has been published [14].

REFERENCES


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