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Instability in Self-Pulsation in Laser Diodes and its Effect on All-Optical Synchonization

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Instability in self-pulsation in laser diodes and its effect on all-optical synchronization

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Abstract. The effect of short- and long-term frequency instability in self-pulsation on all-optical synchronization using a twin-section laser diode is experimentally investigated. Short-term frequency instability broadens the unlocked full width at half maximum (FWHM) of the fundamental of the rf spectrum of the self-pulsating laser diode. We show experimentally that the value of the unlocked FWHM, and thus the level of short-term instability, has a direct effect on the optical power required to maintain synchronization. A novel means of reducing the FWHM is presented, based on a reflective transmission line stub connected to the absorber of the twin-section self-pulsating laser diode in use. A reduction of up to 5 dB in the average optical power required for effective synchronization is observed. Long-term frequency instability can prevent synchronization from taking place because of the limited lock-in frequency range of a self-pulsating laser diode. It is shown that for the devices used here, the dominant cause of long-term instability is temperature. A new method of sensing the temperature in a twin-section laser, called absorber current temperature sensing, which reduces the measured unsycnchronized frequency drift by more than 5:1, is demonstrated. The results have important implications for the design of new all-optical synchronization subsystems, based on self-pulsating laser diodes.

Subject terms: self-pulsation; optical synchronization; twin-section laser diodes; temperature control.

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1 Introduction

The development of very high capacity transmission and switching systems for future communications networks is being actively pursued. As a result, the demand for all-optical functional devices to overcome the speed and architectural limitations of electronics is increasing. One important function in communications switching and transmission systems is synchronization, the most common example of which is timing extraction.

Recently, all-optical synchronization and timing extraction has been demonstrated in a number ways. Among the more popular methods proposed have been electro-optic oscillators[1,2] or, alternatively, the use of an external optical cavity or optical delay loop.[3,4] The approach that has received the most attention, however, is the use of a self-pulsating laser diode for optical timing extraction. This was first demonstrated[5] at a bit rate of 196 Mbit/s, and more recently, the bit rate has been extended[6] to 5 Gbit/s using lasers where the self-pulsation mechanism is passive Q-switching. A new form of self-pulsation in distributed feedback (DFB) laser diodes has also been reported[7,8] with self-pulsation frequencies up to 30 GHz, whereas timing extraction using such lasers has been demonstrated[9] at 18.6 Gbit/s.

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Self-pulsating laser diodes have also been used for all-optical synchronous frequency division[10,11] and multiplication.[12] In addition, a number of applications that can utilize synchronous optical frequency division and multiplication have also been demonstrated, including all-optical clock distirbution[13] and timing extraction from a data signal to provide a submultiple of the bit rate clock for demultiplexing.[14]

The underlying principles of self-pulsation have been explored in detail by a number of authors (for example, Ref. 15), and a method of stabilizing self-pulsation for pulse generation systems has been demonstrated using a feedback technique.[16] The specific requirements for self-pulsating devices used for synchronization, however, have not been examined in depth. Presently the only conditions for effective synchronization are that the self-pulsating laser operates at the source wavelength in use and at the appropriate self-pulsating frequency. If these devices are to be used in actual systems, however, there is a need to explore the nature of synchronization in greater detail and establish what factors influence it.

One such factor is instability in the self-pulsation frequency or period. It is possible to define two distinct types of instability. The first type is short-term instability, which results from the timing jitter and phase noise that is inherent in the physical self-pulsation mechanism.[16] Short-term instability causes a broadening of the full width at half maxi-

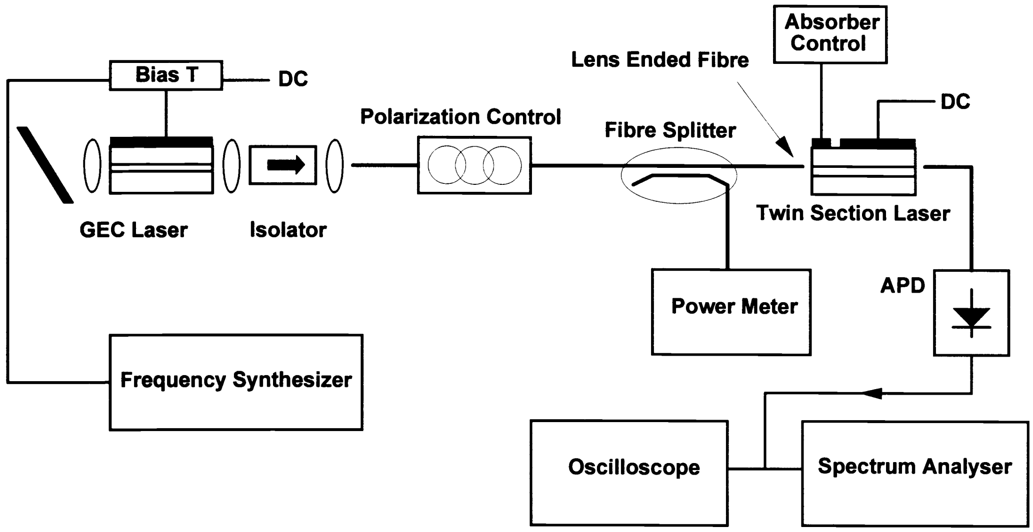

Fig. 1 Experimental setup.

mum (FWHM) of the unlocked self-pulsation rf spectrum. For short-term instability, the magnitude of the fluctuation in the self-pulsation period is considerably smaller than the value of the period itself and occurs over a time interval that has the same order of magnitude as the period. The second type of instability, *long-term* instability, is caused by a slow drift in the self-pulsation frequency, which results from thermal effects and dc bias supply drifts. Long-term instability is also characterized by a fluctuation in the self-pulsation period. However, although this fluctuation is again only a fraction of a self-pulsation period in value, it occurs over a time interval that is at least several orders of magnitude larger than the period. It is thus possible to distinguish between short- and long-term instability when observing the self-pulsation rf spectrum experimentally.

2 Effect of Short-Term Instability on All-Optical Synchronization

In this section, the value of the self-pulsation FWHM is measured experimentally to provide a relative indication of the level of short-term instability. It is shown that for the devices in use here, the value of the FWHM, and thus the level of short-term instability, varies over the range of self-pulsation frequencies. Furthermore, it is demonstrated that the value of the unlocked self-pulsation FWHM has a direct effect on the optical input power needed to achieve synchronization.

2.1 *Experimental Setup*

The experimental setup in this and later sections is shown in Fig. 1. The self-pulsating laser used is a twin section In GaAsP BH device with a length of 500 μm and a 4:1 gain to absorber section length ratio. This device exhibits strong self-pulsation when the absorber is operated within the self-pulsation regime.[17] The self-pulsation frequency can be controlled by the bias applied to each section of the laser.

The source laser shown in Fig. 1 is used to provide an optical clock signal for optical synchronization. This laser is a mode-locked InGaAsP buried heterostructure (BH) laser operating in a tunable grating external cavity. Light from this grating external-cavity laser is coupled to the self-pulsating laser using an 8-μm (radius) lens-ended single-mode fiber. Polarization control and optical isolation are used. The output wavelength of the grating external cavity laser is adjusted so that it coincides with one of the longitudinal modes of the self-pulsating laser diode. Both lasers are temperature controlled to within ± 0.1°C. An avalanche photodiode with a bandwidth greater than 1.8 GHz is used to observe laser outputs on a spectrum analyzer and oscilloscope.

2.2 *Variation in the Unlocked Self-Pulsation FWHM*

The FWHM of the fundamental component of the rf spectrum of the unlocked self-pulsation was measured as a function of the absorber voltage and current, using a spectrum analyzer. At each value of absorber voltage and current, the self-pulsation frequency was also noted. The gain section current was fixed at 83 mA. It was found that the FWHM varies widely over the range of the self-pulsating frequencies. The variation of the FWHM as a function of the self-pulsation frequency is shown in Fig. 2. The minimum FWHM is 273 kHz at 440 MHz and the maximum FWHM is 11.1 MHz at 583 MHz. The ratio of the maximum to minimum value of the FWHM is in excess of 40:1.

2.3 *Effect of the Unlocked FWHM on Synchronization*

To examine how short-term instability affects optical synchronization the grating external cavity laser was used to provide a mode-locked input signal to synchronize the self-pulsating laser diode. The pulse duration, observed on a 20-GHz *p-i-n* photodiode, was maintained at less than 75 ps. The mode-locked laser output frequency was set at a number of values in turn and at each mode-locked frequency synchronization between the mode-locked input signal and the self-pulsating laser diode was achieved. At each frequency used, the absorber voltage was adjusted to achieve the lowest noise floor level for the fundamental component of the synchronized self-pulsation signal. At all of the frequencies used, the gain section current of the self-pulsating laser diode was

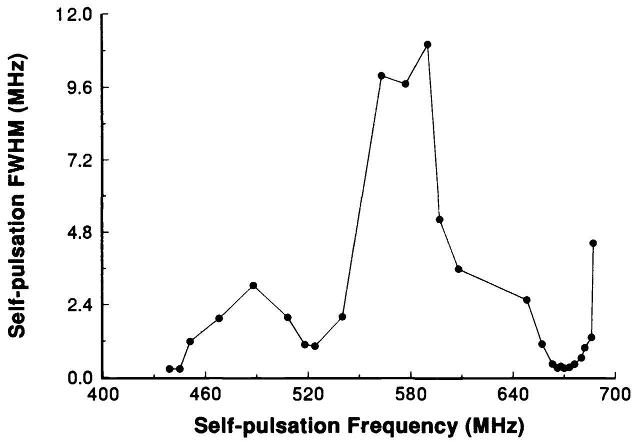

Fig. 2 Variation of the FWHM with the unlocked self-pulsation frequency.

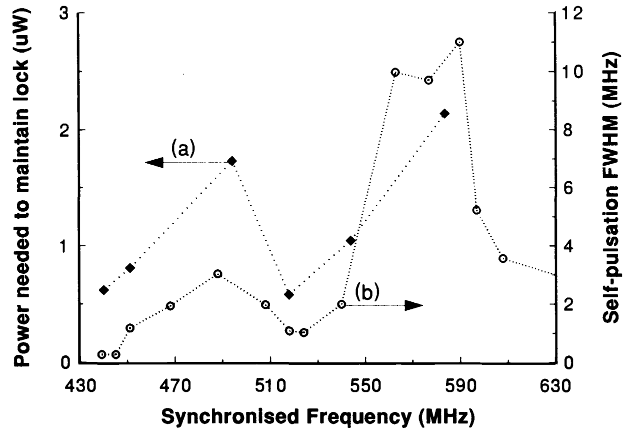

Fig. 3 Plot (a) shows the input optical power needed to maintain synchronization versus frequency. The variation of FWHM with frequency is also shown in plot (b) for comparison.

fixed at 83 mA, and the operating wavelength of the mode-locked laser was adjusted to match the same longitudinal mode of the self-pulsating laser diode.

The synchronized mode-locked and self-pulsation signals were monitored on a twin-channel oscilloscope triggered on the mode-locked input. The mode-locked input optical power was then reduced to a level at which synchronization was just lost. Figure 3 shows the variation in the value of the input optical power needed to just maintain synchronization as a function of the synchronization frequency. The variation of the FWHM is also plotted in Fig. 3 for comparison, as an indication of the level of short-term instability. For low values of FWHM, the input optical power required is about 0.6 μW (at 440 MHz), whereas at frequencies at which the unlocked FWHM is higher, the input power required is larger; for example, at 583 MHz, where the FWHM is greater than 10 MHz, the input optical power needed is 2.14 μW. Operating at a frequency at which the FWHM is close to maximum therefore involves a power penalty because an extra 5.5 dB of optical power is needed to maintain synchronization. Such a power penalty would be very significant for a transmission system in which the operating span is attenuation limited.

It has been previously shown that the value of the noise floor relative to the level of the synchronized fundamental component varies with the input optical power.[10] Above a certain input optical power level, saturation occurs and the level of the noise floor does not improve, whereas below this power level, the noise floor level increases as the input optical power is decreased. For the same input optical power, the relative noise floor was measured at two operating frequencies, one with a low unlocked FWHM value (440 MHz) and the other with a high FWHM value (583 MHz). For an input optical power of 3 μW, the noise floor is 42 dB below the synchronized peak level at 440 MHz, whereas at 583 MHz, the noise floor is 31 dB below the synchronized peak level. This demonstrates that if the optical power available for synchronization is limited, synchronization quality will suffer if the self-pulsating laser is operated at a frequency at which the unlocked FWHM is large.

A number of similar self-pulsating lasers were investigated in this manner. The variation in the value of the FWHM with the self-pulsation frequency was found to be device dependent. For all of the lasers, however, a clear correlation was observed over the self-pulsation frequency range between the magnitude of the FWHM and the slope of the absorber voltage versus self-pulsation frequency characteristic. The measurement of dependence of the optical input power needed for synchronization on the value of the FWHM in use was also repeated, yielding similar results.

3 Use of a Reflective Transmission Line Stub to Reduce Short-Term Instability in Self-Pulsation

A novel technique is presented, which is shown experimentally to reduce the FWHM and thus short-term instability. The effect of a reduction in short-term instability on all-optical synchronization is also investigated. The technique uses a reflective transmission line stub connected to the absorber of a twin-section self-pulsating laser diode.

3.1 *Experimental Setup*

The experimental setup is very similar to that used in the previous section (Fig. 1). The significant addition in this experiment is that a microwave bias-T is used to connect a length of low-loss 50-Ω coaxial cable, acting as a transmission line stub, to the absorber contact. This transmission line stub may be in either one of two states, reflective or nonreflective, using an open circuit or 50-Ω termination, respectively. Once again the self-pulsating laser used is a two-section InGaAsP BH device with a length of 500 μm and a 4:1 gain to absorber section length ratio, while the source laser for synchronization is a mode-locked InGaAsP BH laser operating in a tunable grating external cavity.

3.2 *Influence of a Reflective Stub on Self-Pulsation*

It is known that when a twin-section laser self-pulsates, a pulse-like electrical signal, at the self-pulsation repetition frequency, appears at the laser contacts. This signal was used previously for optoelectronic timing extraction at the absorber of a twin-section semiconductor optical amplifier.[18] In this experiment, the signal at the absorber contact is used to provide an electrical input to the transmission line stub.

This signal can then be reflected back to the absorber, depending on state of the stub termination. The signal at the absorber contact is used in preference to that at the gain contact because measurements on the laser diodes used here have shown that the peak-to-peak electrical level at the absorber contact is higher than that at the gain contact. Furthermore, the absorber requires a lower electrical level for effective synchronization because absorption is more sensitive to variations in electron density than gain.[19]

It is found that the presence of a reflective transmission line stub alters the relationship between the unsynchronized self-pulsation frequency and the absorber voltage. The absorber voltage versus self-pulsation frequency characteristic is shown in Fig. 4 for the reflective and nonreflective cases for a 1-m-long stub. When the stub is correctly terminated and is thus nonreflective, the self-pulsation frequency is a continuous function of the absorber voltage and all values of self-pulsation frequency are possible between 414 and about 714 MHz. When the stub is reflective, the self-pulsation frequency is quantized. If the optical output of the self-pulsating laser diode is observed on a spectrum analyzer, then as the absorber voltage is increased, the self-pulsation undergoes a series of discontinuous jumps in frequency. Within one of the quantized states, the dependence of the self-pulsation frequency on the absorber bias voltage is also reduced.

It is found that the quantized self-pulsation periods/frequencies are those that are close to a submultiple of the round-trip delay. The estimated round-trip delay for the 1-m reflective stub is approximately 10 ns. For this laser, the lowest frequency allowed is in the range 398 to 403 MHz, an average period of 2.49 ns, or approximately one quarter of the round-trip delay. The other quantized periods/frequencies in Fig. 4 correspond to one fifth of the round-trip delay and so on.

The use of a reflective stub also has a profound effect on the unsynchronized self-pulsation FWHM. To demonstrate this a 1-m-long stub was again used, with a self-pulsation frequency of about 500 MHz. The results are illustrated in Fig. 5, where trace (a) shows the self-pulsation fundamental rf spectrum with a nonreflective stub at 498 MHz, and trace (b) shows the same fundamental with a reflective stub. When the stub is nonreflective, the measured FWHM at 498 MHz is approximately 4 MHz, compared with only 50 kHz when the stub is reflective. Alternative shorter stub lengths were also investigated, with equivalent results.

Within one of the quantized states, the FWHM also varies. This is shown in Fig. 6 for a quantized self-pulsation frequency near 500 MHz. The lowest values of FWHM occur at the lowest self-pulsation frequency within a quantized frequency state. As the absorber voltage is increased, the FWHM begins to increase, reaching a maximum at the highest self-pulsation frequency within a permitted range. A further increase in the absorber voltage causes the self-pulsation frequency to jump up to the next quantized state.

An explanation for these effects is that the returning electrical pulse defines the point in time at which an optical pulse is emitted, provided that the electrical pulse arrives back in time just before the optical pulse would have been spontaneously emitted. This process continues on subsequent periods so that the self-pulsation frequency is defined by a submultiple of the round-trip delay rather than by the buildup of the carrier density within the device. As a result, the self-pulsation frequency becomes quantized and the interpulse timing jitter is reduced, thus reducing the observed FWHM.

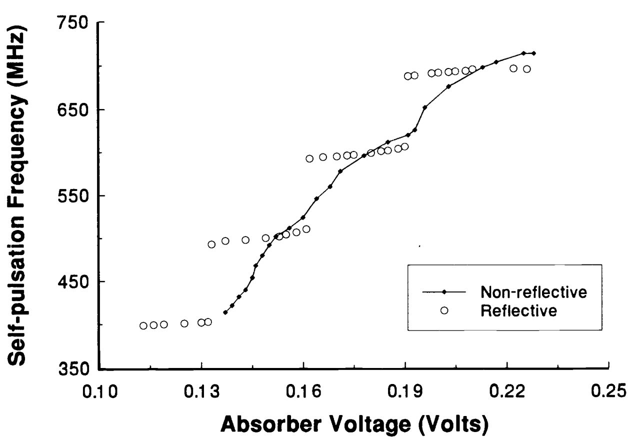

Fig. 4 Influence of a reflective and a nonreflective transmission line stub on the absorber voltage versus self-pulsation frequency characteristic.

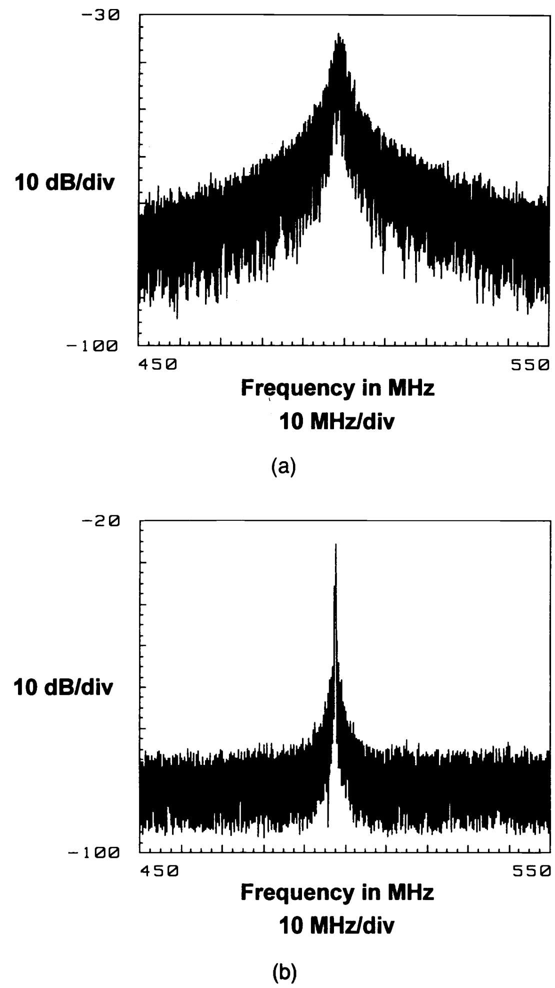

Fig. 5 Effect of transmission line stub on the unsynchronized self-pulsation FWHM at 498 MHz for (a) a nonreflective stub (50-Ω termination) and (b) a reflective stub (open-circuit termination).

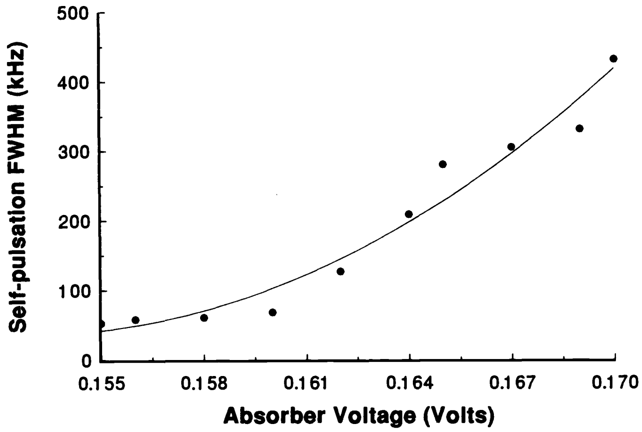

Fig. 6 Variation of the FWHM with absorber voltage for a 1-m resonant stub around 500 MHz (a period equal to a fifth of the round-trip delay).

3.3 *Influence of a Reflective Stub on All-Optical Synchronization*

The effect of a reflective stub on optical synchronization was also investigated, again with a 1-m reflective stub. The mode-locked grating external cavity (GEC) laser (Fig. 1) was adjusted to produce pulses with a repetition rate of 498.1 MHz and a pulse width less than 75 ps at a bias current of 13.17 mA and a modulation level of +22 dBm. With the stub correctly terminated and thus nonreflective, for a gain section current of 83 mA, the self-pulsating laser diode was synchronized to the mode-locked source signal. This was achieved by adjustment of the GEC laser wavelength and polarization and by slight fine tuning of the absorber voltage, which had an optimal value of 0.149 V. The average optical injection power into the self-pulsating laser diode was estimated to be 4.1 μW.

Without any alterations of the source wavelength, power, or polarization, the stub termination was open circuited. The optimal absorber voltage for synchronization was reduced to 0.138 V. The most likely cause of this reduction is the effect of the extra carriers injected into the absorber by the reflected electrical signal from the reflective stub. In both the nonreflective and reflective cases the fundamental of the synchronized self-pulsation was monitored and is shown in Fig. 7. The level of the noise floor relative to the peak of the synchronized self-pulsation fundamental was used previously as an approximate measure of the quality of synchronization.[10] In trace (a) in Fig. 7, with a nonreflective stub, the synchronized self-pulsation has a relative noise floor of 42 dB. In trace (b) in Fig. 7, however, when the stub is reflective, the relative noise floor is 51 dB, demonstrating the improvement in synchronization that can be achieved.

The minimum power needed to achieve synchronization with and without a reflective stub was also determined. The onset of synchronization was monitored in time on a dual-channel oscilloscope, displaying both the GEC laser modulating signal and the self-pulsation output signal. Without a reflective stub, the minimum average optical injection power required is 1.5 μW, and with a reflective stub, the power required falls to 0.5 μW, a reduction of 5 dB.

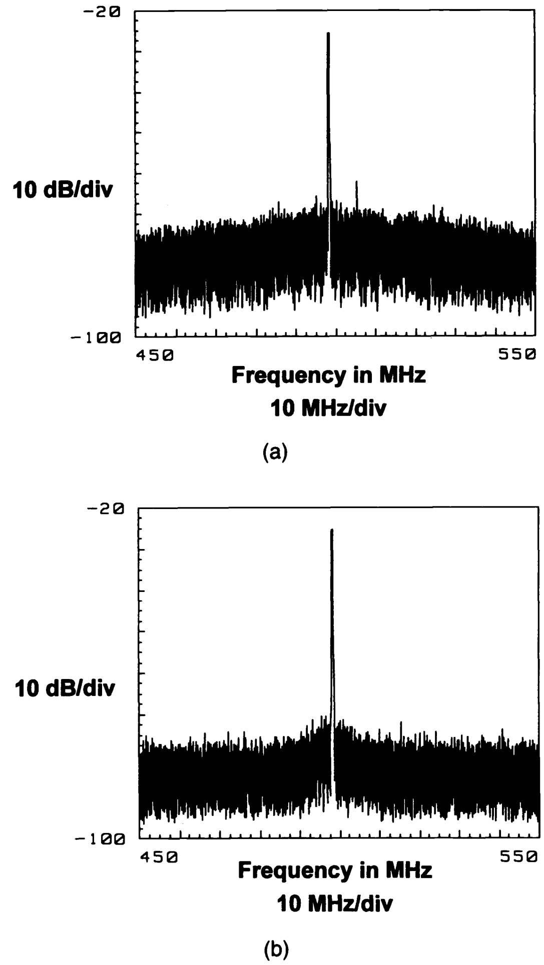

Fig. 7 The spectrum of the synchronized self-pulsation fundamental at 498.1 MHz for (a) a nonreflective stub (50-Ω termination) and (b) a reflective stub (open-circuit termination).

These improvements are significant in a number of ways for example, the reduction in the optical input power needed for effective synchronization is important because many modern transmission systems have an attenuation-limited operating span. Furthermore, the reduced dependence of the unsynchronized self-pulsation frequency on the diode bias will simplify the design of stable bias circuitry for a self-pulsating laser diode used in an actual all-optical synchronization subsystem.

4 Long-Term Self-Pulsation Frequency Drift and Its Control

Long-term instability in a self-pulsating laser diode results in a drift in the frequency of self-pulsation, and this drift can prevent synchronization from taking place. This can occur if the frequency drift exceeds the limited lock-in frequency range of a self-pulsating laser diode. If the unlocked self-pulsation frequency is initially adjusted so that the optical input signal frequency lies within the self-pulsating lock-in range, then synchronization will take place. If the self-pulsation frequency drifts, however, synchronization will not take place if the optical input frequency lies outside the shifted lock-in range, after drift has occurred.

4.1 *Causes of Frequency Drift*

For the twin-section laser diode used here, the gain section current, absorber section voltage, and laser temperature are all controlled but are sources of drift in the self-pulsation frequency.[17] Using a similar experimental setup to that outlined in Sec. 2, the causes of self-pulsation frequency drift were investigated. First, the inherent stabilities of the gain and absorber bias sources and the temperature control system were measured over a period of time and were found to be within ± 3.5 μA, ± 150 μV, and ± 0.1°C, respectively. These values are similar to the typical stabilities reported in the literature for an experimental setup such as this.

Next the change in the self-pulsation frequency was measured for a unit change in the gain section current, absorber section voltage, and laser temperature. The results were 19.4 MHz/mA, 3.87 MHz/mV, and 12.3 MHz/0.1°C, respectively. From these results and the measured inherent stabilities, it is estimated that the frequency drift caused by the individual control parameters lies within ± 68 kHz for gain section current, ± 580 kHz for absorber section voltage, and ± 12.3 MHz for temperature control to within ± 0.1°C. Based on these results, it is clear that the dominant contributor to long-term frequency instability is temperature. It also demonstrates that failure to acquire synchronization because of frequency drift is a distinct possibility. For the devices used here, the typical lock-in range is found[10] to be about 30 MHz for a self-pulsation frequency of 440 MHz. This range is only slightly larger than the self-pulsation frequency drift range of 25.8 MHz calculated for the worst case drift in the laser bias and temperature, using the measured stability values.

4.2 *Alternative Temperature Sensing Method*

Conventional laser diode temperature control systems rely on an external feedback sensor, such as a thermistor, to provide a temperature sensing feedback signal. Such systems do not directly sense the temperature of the active region of laser diode.[20] Because of the physical dimensions of a typical feedback sensor, the sensor must be positioned some finite distance from the laser junction. Because of the inherent thermal resistance and thermal capacitance of the laser heat sink mount, a thermal gradient and a thermal time constant exists between the active region of the laser and the sensor, which degrades the ultimate temperature stability that can be achieved and thus the ultimate self-pulsation frequency stability.

To improve the temperature stability an alternative temperature control scheme was developed that more accurately senses the temperature variations in the active region of the laser diode, instead of the temperature of the laser mount. This is achieved by monitoring and processing the absorber current to provide a temperature sense signal as feedback for a conventional temperature controller. A similar technique was demonstrated previously for wavelength stabilization, where the forward voltage on a single-section laser diode was used as a feedback signal for temperature control.[20]

In a twin-section laser diode, the gain section current and absorber section voltage are normally fixed for device biasing, leaving the gain section voltage and absorber section current as possible parameters for temperature sensing. To determine which of these two parameters is most effective for use as an indication of active region temperature fluctuations, the sensitivities of these parameters to temperature change were examined. The variation in absorber section current with temperature change was first investigated, keeping all other device parameters constant. The results are shown in Fig. 8(a), from which the average percentage change in absorber current per degree Celsius is estimated to be 0.92%. A similar measurement was then repeated for gain section voltage. The variation in gain section voltage with temperature is shown in Fig. 8(b). The average percentage change in the gain section voltage per degree Celsius is found to be 0.063%. For comparison, the sensitivity of the existing external feedback sensor to temperature change is 0.3% per degree Celsius, substantially less than that of the absorber current. From these results, it is clear that absorber section current is more sensitive to temperature change than gain section voltage and is thus the preferred choice for temperature monitoring. This is to be expected because carrier densities are highly dependent on the temperature of the active region.

4.3 *Demonstration of an Absorber Current Feedback System*

To demonstrate the feasibility of temperature control using the absorber current as a temperature sensing feedback pa-

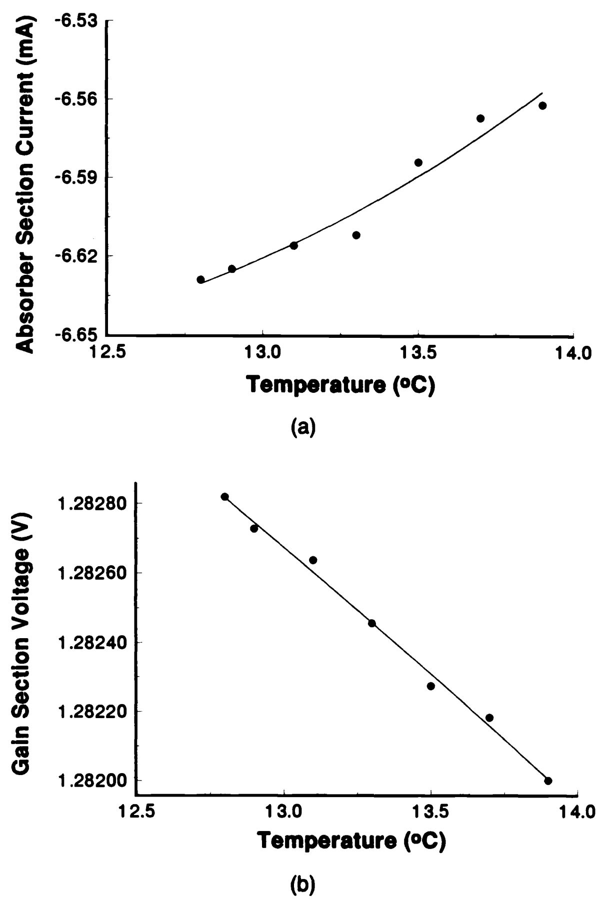

Fig. 8 Measured variation in laser bias values as a function of temperature with (a) absorber section current and (b) gain section voltage. The absorber section voltage and gain section current are fixed in value.

rameter, a novel signal processing system was developed. This system monitors the magnitude of the absorber current and converts this magnitude to a proportional signal that can be used by the existing conventional temperature controller. Using the existing temperature controller is important because it allows for a valid comparison of different temperature sensing methods.

Using the absorber current to sense the laser temperature and using a precision platinum resistance temperature probe, the thermal stability of the laser heat sink was measured over a 60-min period for an initial set temperature of 22.66°C. The results are presented in Fig. 9, which shows that the temperature stability was within ±0.02°C, an improvement of a factor of 5:1 by comparison with conventional temperature sensing.

The stability of the self-pulsation frequency as a function of time was also measured first using conventional temperature sensing and then using absorber current temperature sensing. The frequency stability was measured using a spectrum analyzer over a period of 60 min for a self-pulsation frequency of 600 MHz. The frequency stability with conventional temperature sensing was approximately ±12.5 MHz, whereas the stability using absorber current temperature sensing was found to be better than ±2.5 MHz, again an improvement of about 5:1. Work is ongoing on the optimization of this system to achieve a temperature stability of better than ±0.01°C.

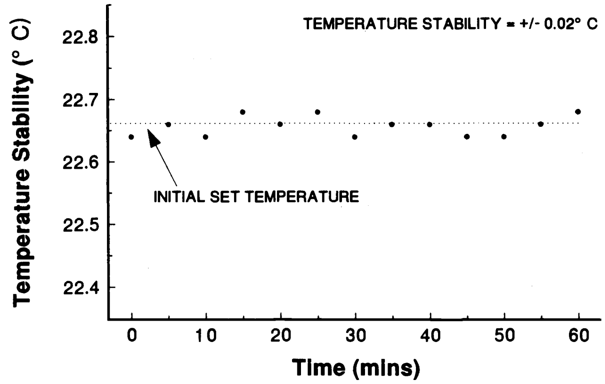

Fig. 9 Measured temperature stability over a 60-min period, using absorber current temperature sensing, for an initial set temperature of 22.66°C.

5 Conclusions

It has been demonstrated experimentally that the short-term self-pulsation stability, indicated by the unlocked self-pulsation FWHM, has a significant effect on the input power needed for synchronization. Therefore in developing new twin-section lasers for all-optical synchronization it is concluded that it is not enough to ensure that the appropriate self-pulsation frequency can be attained to match the input operating frequency. It is important to ensure that the FWHM of the unlocked self-pulsation is low at the operating frequency in use to avoid a power penalty.

We have also demonstrated experimentally that a reflective transmission line stub can have a profound effect on the characteristics of the unsychronized self-pulsation in a twin-section laser diode. The self-pulsation frequency is quantized and the dependence of the self-pulsation frequency on the device bias is reduced. Most importantly, there is a dramatic reduction in FWHM of the unsynchronized self-pulsation. With all-optical synchronization, the reduction in the FWHM results in an improvement of 9 dB in the relative noise floor, which is a measure of the quality of all-optical synchronization. Furthermore, the use of a transmission line stub reduces by 5 dB the minimum average optical input power needed to cause synchronization, which is of significant benefit in a transmission system where the operating span is attenuation limited. Because this is the first time that such an improvement has been demonstrated, we believe that further improvement is possible. For this reason, we believe that the technique is suitable for incorporation into an all-optical synchronization system.

For long-term instability, it is concluded that for the twin-section lasers used here, temperature change is the most significant cause of frequency drift. The use of absorber current temperature sensing as a new method of accurately sensing the temperature of the active region of the laser has been shown to be both practical and worthwhile with a 5:1 reduction in self-pulsation frequency drift. For the observed lock-in range for optical synchronization, the self-pulsation frequency stability achieved using this new technique can eliminate synchronization failure caused by frequency drift. Note, however, that once synchronized, the effects of temperature drift are not eliminated. Although self-pulsation frequency drift can no longer take place, we have observed that slight bias and temperature changes can alter the relative synchronized noise floor. Further research is needed to establish the effect of thermal and bias drift on the quality of synchronization, even though frequency drift no longer takes place.

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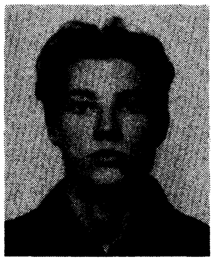

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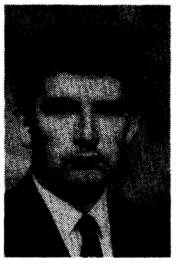

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