Paper

All-optical intensity noise suppression for solid-state and semiconductor lasers

Márk Csörnyei, Tibor Berceli, and Tamás Marozsák

Abstract—This paper will report on a new all-optical technique of relative intensity noise (RIN) suppression for solid-state and semiconductor lasers. The new scheme we have used is based on an unbalanced Mach-Zehnder interferometer (UMZI), which is able to cancel the intensity noise enhancement at relaxation resonance. Although the relaxation oscillations frequency and the level of the corresponding noise maximum are extremely different concerning solid-state microchip lasers and semiconductor laser diodes, the proposed passive noise suppression is well suited for both types of laser sources used in telecommunication. The UMZ fiber interferometer solution for solid-state lasers demonstrated hereunder was generalized and deployed in case of semiconductor lasers as well.

Keywords— *laser noise, neodymium:solid lasers, optical communication, semiconductor lasers.*

1. Introduction

The optical generation of microwaves by using two-frequency solid-state lasers (SSLs) presents an efficient way of generating and transmitting high quality local oscillator signals in fiber-radio and radar systems. Diode pumped microchip lasers like Nd:YVO_4 can operate in two or three longitudinal modes with a frequency difference defined by the crystal geometry. After optical detection these modes provide beat notes in the microwave and millimeterwave range, which can be used as high-purity signals for further processing in telecommunication systems.

Due to their outstanding phase-noise characteristics and high output power, rare-earth doped solid-state lasers can be put to use in distribution networks and common antenna television (CATV) systems as well.

However they show a significant intensity noise enhancement at the relaxation oscillations quite close to the optical carrier. In order to reduce this resonance term in the relative intensity noise (RIN) spectrum, a number of opto-electronic feedback loops have been reported in the literature. Kane [1] and Harb [2] have designed electronic feedback systems for intensity noise reduction in diode pumped Nd:YAG lasers. In the same way, Geronimo [3] and Taccheo [4] have examined the RIN reduction in an ytterbium-codoped erbium glass laser. Concerning our previous report, Csörnyei *et al.* [5], significant noise suppression was achieved by using opto-electronic feedbacking in case of a Nd:YVO_4 microchip laser.

In this paper we present a new all-optical solution for intensity noise suppression. Instead of using an electronic control loop, an unbalanced Mach-Zehnder fiber interferometer (UMZI) with a free spectral range (FSR) of 2 MHz is employed to put down the noise peak at the relaxation resonance.

The new passive noise cancellation scheme we have mentioned in the preceding discussions can be universalized and applied concerning semiconductor laser diodes as well. Similarly to microchip lasers the RIN is one of the most important impairments in laser diode based optical transmitters too. In that case the relaxation oscillation has got much higher frequency and damping which results in a quite broad and flat noise increment in the microwave domain. Due to these characteristics the laser diode intensity noise is not a limiting factor in optical generation of high quality microwave signals like in solid-state lasers, but significantly raises the overall noise floor of the optical link. Concerning this motivation it is also worth dealing with RIN suppression of laser diodes by using an extended version of an unbalanced fiber interferometer.

The paper consists of two parts. In the first part possible noise reduction is discussed in case of a Nd:YVO_4 microchip laser, the second shows the extension of our approach to semiconductor laser diodes. The structure is as follows. Section 2 presents the optical subsystem containing a Nd:YVO_4 SSL and the all-optical noise suppression. Sections 3 and 4 describes the measurement and simulation results of a laser diode RIN reduction. Section 5 summarizes the results so far and further possible efforts in this field.

2. UMZI for noise suppression of Nd:YVO_4 microchip laser

2.1. Characterization of the Nd:YVO_4 SSL system

The laser system we considered and the optical spectrum of the two frequency microchip laser output can be seen in Figs. 1 and 2, respectively. The two longitudinal modes of our Nd:YVO_4 crystal laser are 60 GHz apart. This dual wavelength operation makes use of this type of solid-state lasers in optical generation of microwave and millimeter-wave signals.

The laser crystal is pumped optically by an SCT100-808-Z1-01 high power laser diode at a wavelength of 808 nm.

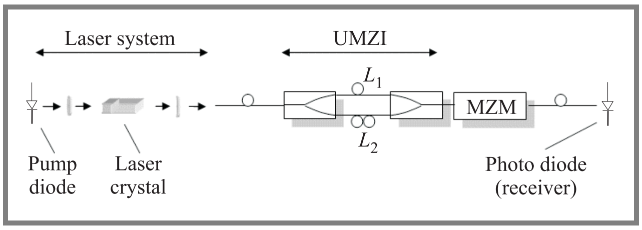

Fig. 1. Diode pumped solid-state laser followed by an UMZI for intensity noise cancellation. The information signal to be transmitted can be modulated on to the optical carrier by a Mach-Zehnder modulator. (The photodiode represents one of the possible receivers in the optical network.).

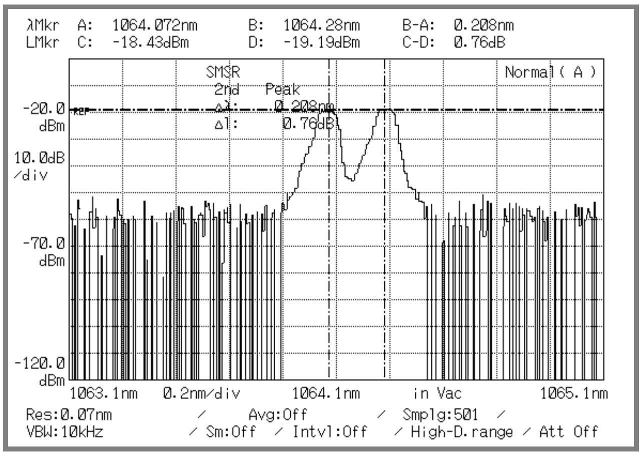

Fig. 2. The two longitudinal modes of the Nd:YVO_4 solid-state laser with a frequency difference of 60 GHz. It was captured by an Anritsu MS9710B optical spectrum analyzer. Measurement conditions: wavelength – 1064 nm, resolution bandwidth – 0.7 nm.

The pump diode is temperature stabilized by a Peltier element and an LDT-5412 temperature controller. The laser diode had a maximal output power of 1.4 W. The pumping light is focused on the laser crystal input mirror by a Thorlabs C440TM-B lens. Being pumped the Nd:YVO_4 crystal produces an output power of 200 mW at the wavelength of 1064 nm, which is focused into the optical fiber.

Figure 3 shows the measured relative intensity noise peak of the solid-state laser. The noise level at the relaxation oscillations is 40 dB higher than one outside the resonance region. The noise peak was captured by an InGaAs photodiode followed by a 5 kΩ gain transimpedance amplifier. The detector was illuminated by a 10 mW fraction of the crystal output power. The maximum value of the noise curve was –50 dBm on the 50 Ω input impedance spectrum analyzer. Taking account of the 5 kΩ transimpedance of the receiver, the 10 kHz resolution bandwidth of the spectrum analyzer, and the $\eta = 0.8$ quantum efficiency of the InGaAs photodiode material at 1064 nm, a relative intensity noise value of –70 dBc/Hz can be evaluated. Both the frequency of the relaxation oscillations and the power of the noise peak depend on the laser diode pump power. In Fig. 3 pumping the solid-state laser by a diode power of 350 mW the intensity noise maximum had a frequency

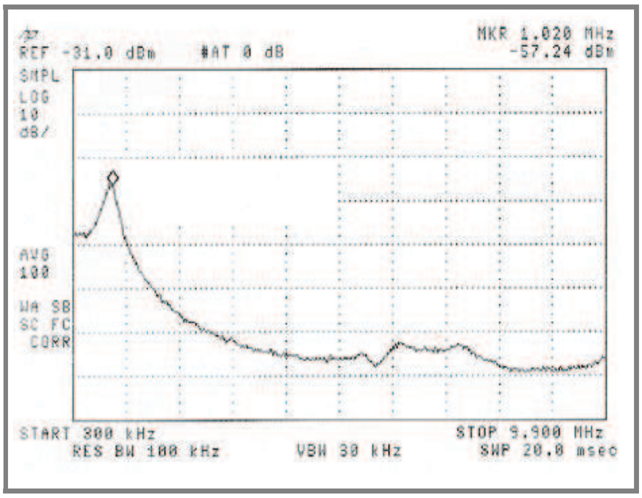

Fig. 3. Intensity noise at the relaxation frequency of 1020 kHz. The pump power was 350 mW (600 mA bias current across the pump diode). The measurement conditions are: resolution BW = 100 kHz, video BW = 30 kHz, 100 point video averaging, input attenuation = 0 dB.

difference of 1 MHz to the optical carrier. When using a constant pump power, as in normal applications, the frequency of the relaxation oscillations does not change, and thus an interferometric noise reduction is feasible.

2.2. UMZI design considerations and suppression results

Concerning the noise suppression scheme in Fig. 1, the laser output is coupled into an unbalanced Mach-Zehnder interferometer. The input 3 dB coupler divides the laser signal into the two arms of the UMZI. Properly setting the time delay difference between the two signal paths the output 3 dB coupler combines the signals with a phase shift of 180° at the relaxation oscillations frequency. Exploiting this time delay difference, the intensity noise peak can be appreciably reduced. To obtain a 0.5 μs delay difference for noise suppression at the 1 MHz resonance frequency of SSL, we considered an UMZI with a free spectral range of 2 MHz. Equation (1) shows the required fiber lengths difference for such purposes [6]:

$$\tau = T_2 - T_1 = \frac{n}{c}(L_2 - L_1) = \frac{1}{\mathrm{FSR}} \Rightarrow \Delta L = \frac{c}{n}\ 0.5\ \mu\mathrm{s} = 100\ \mathrm{m}. \tag{1}$$

According to Eq. (1) we need a 100 m fiber length difference in case of common fiber materials (refractive index: $n = 1.5$). The transfer function of the UMZI is depicted in Fig. 4. By appropriate tuning of the FSR the rejection frequency is selected at 1 MHz. Passing through the delay lines the noise enhancement at the relaxation resonance is canceled in the output 3 dB coupler. The suppression ratio at the rejection frequencies is defined by the attenuation difference of the two arms in the UMZI. Keeping this difference low an optical rejection of 30 dB is feasible. Figure 5 shows the possible intensity noise reduction at the relaxation oscillations of the Nd:YVO_4 solid-state laser.

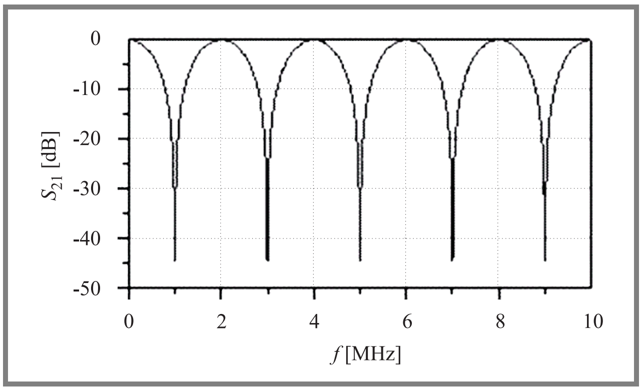

Fig. 4. The transfer function of an unbalanced Mach-Zehnder interferometer (FSR = 2 MHz) for noise reduction in Nd:YVO_4 SSLs. The required fiber length difference calculating with a refractive index of $n = 1.5$ is: $\Delta L = 100$ m.

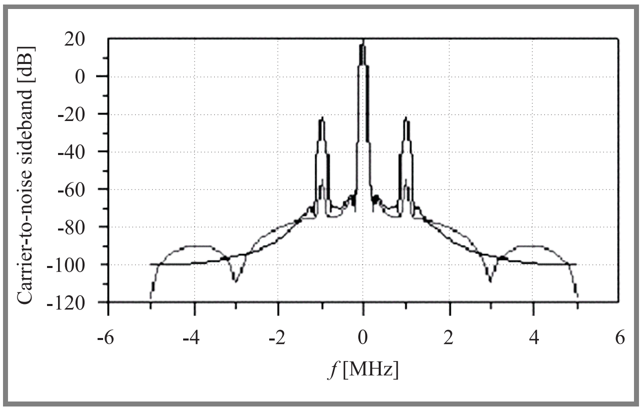

Fig. 5. The feasible intensity noise suppression at the frequency of the relaxation oscillations. There is a possible suppression of 30 dB. The further improvement is limited by the attenuation difference of the two arms in the fiber interferometer and by the damping in the photon density impulse response of the Nd:YVO_4.

The relative intensity noise peak we are dealing with can be characterized by the photon density impulse response which is a reply to small perturbations in the laser population inversion. As it is shown in Eq. (2) the photon density impulse response is a damped sinusoidal function which results in a spectral broadening around the relaxation oscillations frequency (Fig. 3):

$$\Delta\phi \approx \exp\left(\frac{\sigma c \phi}{2}\right) t \sin\left[\sigma c (\phi n)^{1/2} t\right]. \tag{2}$$

In Eq. (2) σ is the emission crossection, n the electron population density and ϕ the photon density. Based on Eq. (2) the frequency of the oscillation can be expressed by the intercavity power density, $I = c\phi h\nu$, and the photon decay time: τ_c [9]. The frequency of the relaxation oscillations is represented in Eq. (3):

$$\omega = \sqrt{\frac{\sigma I}{\tau_c h\nu}}. \tag{3}$$

Table 1 presents the parameters necessary to the impulse response calculations in case of the Nd:YVO_4 crystal laser. The calculated photon density impulse response is depicted in Fig. 6. Due to the spectral broadening caused by the damped look of the impulse response there is a slight difference to the ideal suppression in Fig. 5.

Table 1
Parameters of 1.1% doped Nd:YVO_4

Attenuation	Threshold power	Emission crossection	Photon decay time	Calculated power density*)
α [1/cm]	P_{ib} [mW]	σ [cm^2]	τ_c [s]	I [W/cm^2]
9.2	78	$7 \cdot 10^{-19}$	$3.623 \cdot 10^{-12}$	4.33

*) Considering the crossection area (0.6 mm $\times$ 3 mm) of the crystal.

Equation (3) shows the dependence of the relaxation resonance frequency on the pump power (I: intercavity power density is proportional to the pump power). In our solution compared to the optoelectronic suppression techniques the pumping rate is kept constant and thus a noise reduction fixed to an effective pumping rate is feasible.

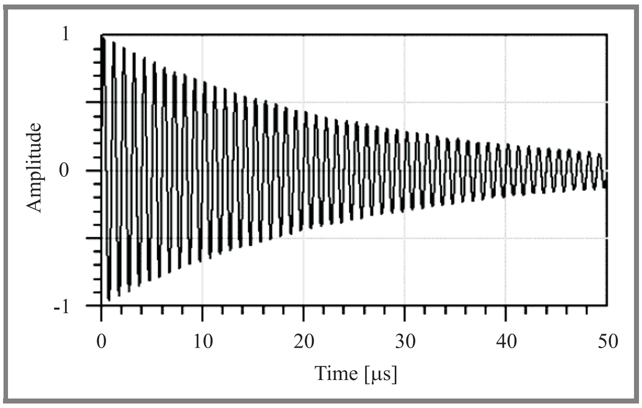

Fig. 6. The photon density impulse response of the Nd:YVO_4 solid-state laser crystal. Damping causes spectral broadening at the relaxation oscillations frequency.

The noise cancellation subsystem is followed by a Mach-Zehnder modulator (MZM) in Fig. 1. Placing the external modulator after the UMZI the information to be transmitted can be modulated on to the high quality noise reduced optical carrier.

3. UMZI for noise suppression of laser diodes

The unbalanced Mach-Zehnder interferometer based intensity noise suppression scheme for laser diodes is depicted in Fig. 7. In that structure we have utilized an InGaAsP multi-quantum well (MQW) Fabry-Perot laser diode. The output power and the operation wavelength were 0.1–2 mW and 1310 nm, respectively. The pigtailed output of the laser diode was connected to the interferometer, which consisted of two Kamaxoptic 3 dB (50/50) splitter modules and two SMF-28 type single mode optical fiber in-between.

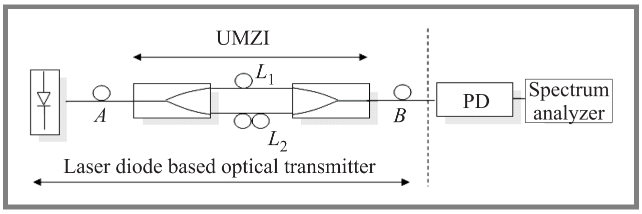

Fig. 7. Two paths unbalanced Mach-Zehnder interferometer for intensity noise suppression of semiconductor laser diodes. The fiber length difference is 1 m.

The intensity noise maximum defined by the relaxation oscillation is at 2 GHz exciting the diode by a bias current of 10 mA. According to Eq. (1) an UMZI path length difference of 0.05 m is required in order to reduce the noise at 2 GHz. A fiber interferometer with a free spectral range of 200 MHz (path length difference: 1 m, $n = 1.5$) was chosen instead because of its higher number of resonance frequencies. Increasing the path length difference between the two fiber arms of the interferometer we will end up with an increased number of suppression points in the noise spectrum, which means a higher average noise reduction.

Actually the UMZI is an optical finite impulse response (FIR) filter which has got only two taps and both of the filter coefficients are +1. Since we only have positive values for the filter coefficients the UMZI behaves as an optically realized low-pass filter with multiple transmission and attenuation bands. The low-pass characteristic is of prime importance because it ensures that the optical carrier itself will not be filtered out.

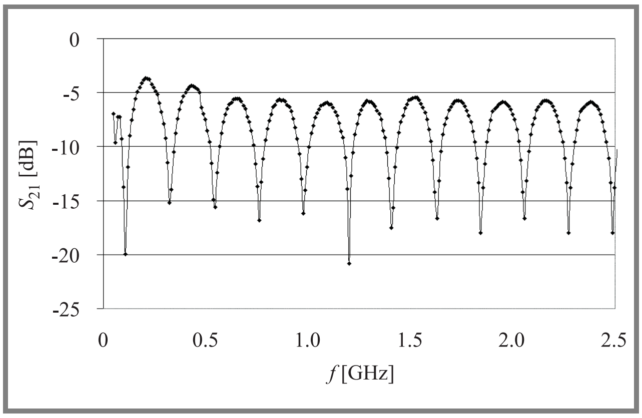

Fig. 8. The measured transfer function of the 200 MHz free spectral range unbalanced Mach-Zehnder interferometer (from A to B in Fig. 7). The fiber length difference of the two SMF-28 type optical fiber was 1 m. The measurement was taken by an HP8722D 50 MHz–40 GHz network analyzer. The measurement signal of the network analyzer was modulated on to the optical carrier by an HP83422A lightwave modulator at point A (Fig. 7) and detected by an HP11982A lightwave converter (1200–1600 nm) at point B (Fig. 7). The UMZI has an average attenuation of around 6 dB which comes from the attenuation of the optical fibers and connectors inside the interferometer. As it is shown there is a noise reduction capability of 15–20 dB at selected resonance frequencies of the UMZI.

Figures 8 and 9 show the measured transfer function of the interferometer discussed above and the achieved noise reduction respectively. As it is shown in Fig. 8 the interferometer has an attenuation of about 6 dB which comes from the attenuation of optical connectors between the laser pigtail, the 3 dB couplers and the fibers. Taking account of this attenuation there is a noise reduction of 8–9 dB at the UMZI resonance frequencies around 2 GHz in Fig. 9. The further suppression is possible at the selected frequencies but the measurement is limited due to the spectrum analyzer noise floor.

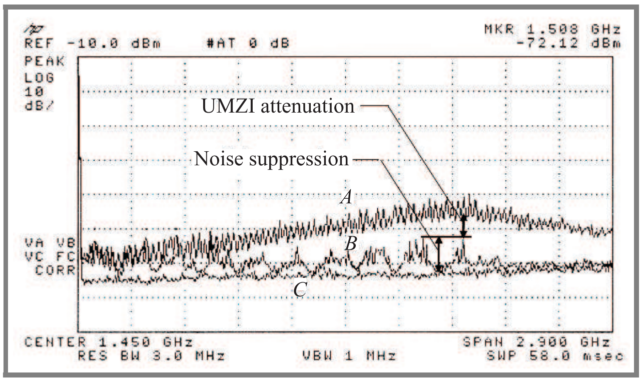

Fig. 9. The measured noise suppression of the UMZI of Fig. 7. A – the relative intensity noise of the investigated Fabry-Perot semiconductor laser diode around 2 GHz (point A in Fig. 7); B – the measured interferometric noise suppression (point B in Fig. 7); there is a periodic noise reduction of 8 – 9 dB, the periodicity corresponds to the 200 MHz FSR of the UMZI; C – the noise level of the measurement system. The results were captured by an HP8593E spectrum analyzer under the following conditions: resolution BW = 3 MHz, no video averaging, input attenuation = 0 dB.

4. Opto-microwave filter

In case of solid-state lasers the noise peak at the relaxation oscillations frequency is limited in a quite narrow bandwidth (noise peak linewidth: 10–50 kHz) and thus interferometric noise cancellation is a good solution. However concerning semiconductor lasers the noise enhancement is a flat and broad maximum around the relaxation resonance. Using UMZI, noise reduction is only possible at selected resonance frequencies of the interferometer (Fig. 9). To achieve overall noise suppression around the relaxation oscillations of the laser diode, the interferometer should be extended with additional fiber arms. It means we should increase the tap number in our optical FIR filter. Placing new lines with different optical delays will result in spectral broadening of the attenuation bands in the filter transfer function.

Figures 10 and 11 present the structure and the calculated transfer function of such an interferometer with three optical paths. As it is shown setting the relative delay of the new arm to 250 ps (fiber length difference: 0.05 m) the broadening of the attenuation band around 2 GHz is feasible.

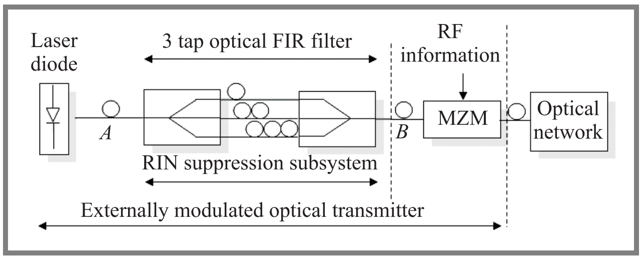

Fig. 10. Three paths interferometric noise suppression system for semiconductor laser diodes. The laser light passing through the interferometric filter can be modulated externally and sent to the optical communication network.

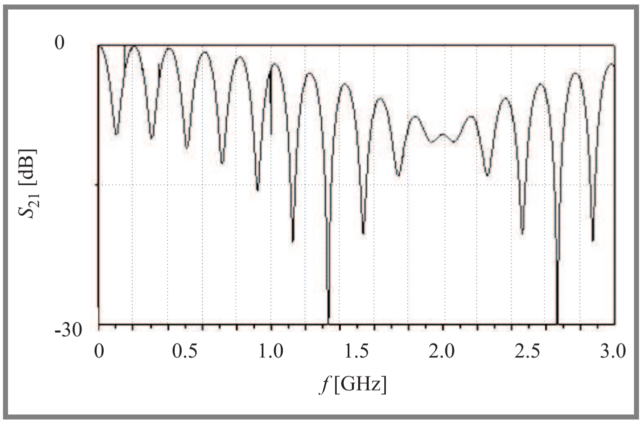

Fig. 11. The calculated transfer function of the interferometric noise cancellation system shown in Fig. 10. There is a 10 dB suppression capability around 2 GHz.

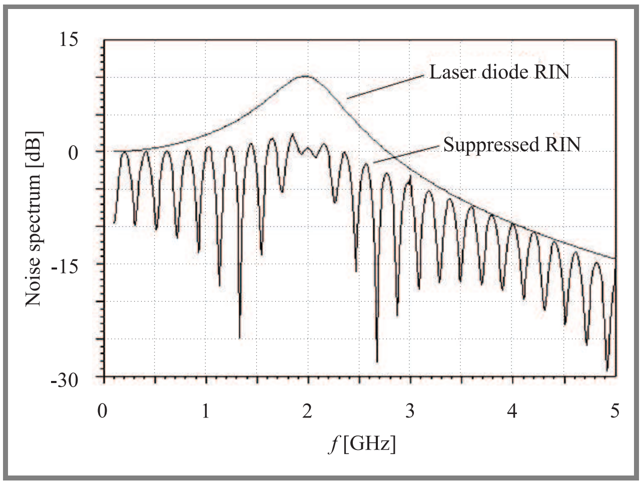

Fig. 12. The calculated noise suppression of a three paths UMZI (Fig. 10). The spectral density function of the laser diode RIN was approximated by the transfer function of a linear system [5]. The possible noise power reduction in this interferometer is 10 dB.

The possible intensity noise suppression by using the discussed interferometer is depicted in Fig. 12. The spectral density function of the laser diode relative intensity noise was approximated by a simple transfer function [5].

When applying additional arms in the interferometric filter, significant improvement takes place in the noise suppression capability of the proposed scheme. Figure 12 shows a 200 MHz attenuation band around the relaxation oscillations which is five times wider than when we use a simple two paths interferometer.

5. Conclusion

In our paper a new method of relative intensity noise suppression for both solid-state lasers and semiconductor laser diodes has been demonstrated.

As we have seen in Section 2, all-optical relaxation resonance cancellation is feasible for solid-state microchip lasers in case of applying an unbalanced Mach-Zehnder interferometer in the laser transmitter section. If the adequate time delay difference between the two arms of the UMZ fiber interferometer is adjusted the noise sidebands of the optical carrier almost disappear.

Concerning the case of semiconductor laser diodes, additional efforts have to be made in the field of filter design in order to achieve sufficient suppression in the band of the noise maximum.

Compared to the optoelectronic suppression techniques there is no need for electronic circuit design and maintainance in our scheme. Since there are only passive devices, the design of biasing and supply systems and the corresponding power consumption is avoidable as well. Due to the all-optical solution, the problem of electromagnetic interference does not need to be faced, which – owing to the low frequency (LF) radio broadcasting – causes major impairments. Furthermore, due to the feedbacking, the application of the well known optoelectronic system causes some noise enhancement outside the suppression region [2, 5], which falls out of our newly introduced approach.

In order to be able to achieve a robust system, precise temperature stabilization of the optical devices is required. In this aspect, integrated optical realization can provide considerable advantages, since the use of simple Peltier-elements will be possible.

Lithium niobate based integrated optics can deliver other benefits as well. Due to the voltage dependence of the refractive index in this material [10], tuning of the delay lines in the unbalanced Mach-Zehnder interferometer by applied voltage is feasible. According to this property a more flexible operation is realizable, where the interferometer can follow the changes caused by the pump power (SSL) or bias current (laser diode) variation of the relaxation oscillation frequency. The requirement of using tunable noise suppression systems can occur in dynamic optical networks where the number of optical nodes and thus the required transmitter power has to be changed.

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