Referenced paper's list

Referenced paper:

M.Csörnyei., T.Berceli, T.Bánky: „Microchip laser RIN suppression for fiber radio applications", *URSI 2002, XXVIIth General Assembly of the International Union of Radio Science*, Maastricht, Netherlands, August 14-17, 2002, No.1848.

M.Csörnyei, T.Berceli, P.R.Herczfeld: „Noise suppression of Nd:YVO4 solid-state lasers for telecommunication applications", *IEEE Journal of Lightwave Technology*, Vol. 21, No. 12, December 2003, pp.2983-2988. L R

Referencing paper:

S. Valling, B. Ståhlberga, Å.M. Lindberg: „Tunable feedback loop for suppression of relaxation oscillations in a diode-pumped Nd:YVO4 laser", *Optics & Laser Technology*, vol. 39, Issue 1, February 2007, pp. 82-85.

Context: „Suppression results around 25–30 dB are demonstrated in the RO frequency range of 500 kHz to 1.5 MHz. These results are comparable to those presented in [4], [5], [6], **[7], [8]**, [9] and [10] in the 100–350 kHz region. "

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NOISE SUPPRESSION RESULTS OF TELECOMMUNICATION LASERS Csörnyei Márk, Ph.D. thesis statements

Noise suppression results of telecommunication lasers

Ph.D. thesis statements

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2008.

Aim and subject of the dissertation

The aim of this dissertation is to present my research results in the field of telecommunication lasers intensity noise suppression, both in case of solid state lasers and semiconductor lasers.

Taking into account short haul optical fibre links, like optical local area networks, optical Local Multipoint Distribution Systems (LMDS) or optical-mobile systems, due to the small fibre attenuation the laser intensity noise overcomes the receiver thermal noise, thus it is the most significant contribution to the photo detector noise floor. It is obvious that strong research is done in the field of laser relative intensity noise (RIN) suppression. My dissertation deals with intensity noise suppression for solid-state and semiconductor lasers. In my work I suggest new noise suppression methods and design technology.

I summarized my results in three thesis points. The first point covers optoelectronic noise suppression of Nd:YVO_4 (neodymium-yttrium orthovanadate) solid-state lasers and its effects. I introduced a new model for the laser in order to ease the optoelectronic feedback system design. The new model based noise suppression loop design was tested by measurements, where I have reached 17dB noise suppression. Applying an optoelectronic feedback loop the suppression of intensity noise at relaxation oscillations is feasible. However feedbacking can cause chaotic oscillations in the laser. In order to avoid bifurcation and chaotic oscillations in photon density the laser dynamic behaviour has to be analyzed. For investigation of the dynamic operation of the laser I had to solve rate equations which present a system of nonlinear differential equations. If one applies an optoelectronic feedback loop the feedback signal acts as an input modulation which turns the equation into a non-autonomous system of nonlinear differential equations. Analysing the mathematical results I could declare a limit for feedback modulation depth in order to avoid chaotic behaviour.

Concerning the second point of my thesis, I submitted a new intensity noise reduction concept for semiconductor laser diodes using Unbalanced Mach-Zehnder Interferometers (UMZI). This kind of interferometers act like periodic filters, which can be exploited in noise suppression. However they have significant phase noise – intensity noise conversion capability which could cause intensity noise growth instead of reduction. Toward concepting a new way of noise suppression I had to calculate the phase-to-intensity noise conversion of such optical structure assuming both phase noise and intensity noise at the input. I calculated the noise conversion both in coherent and in incoherent case. Using this calculations I presented a new design method for UMZI based noise suppression schemes. The results were confirmed by measurement results as well.

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[Csörnyei,2004c] T.Berceli, **M.Csörnyei**, T.Bánky, T.Marozsák, E.Udvary, G.Járó, A. Hilt: „Improvements in Radio over Fiber Systems for Mobile Networks", *IEEE Radio & Wireless Conference, RAWCON 2004*, Workshop paper: Front End Opto-Electronics for Future Radio Communications, Atlanta, USA, September 20, 2004.

The third point of the thesis investigates the problem of using optical finite impulse response filters (FIR) in the application of semiconductor laser noise suppression. I have calculated the phase-to-intensity noise conversion of a simple three tap filter structure. The calculations confirm that using sufficient design considerations we can use this kind of optical-microwave filters for passive noise suppression. Additionally I have analyzed and explained the different phase-to-intensity noise conversion characteristics of the different points of the coherent filter transfer function.

The dissertation here presented is amended by a deep literature survey in the field.

Tentative and analysis methods used in the dissertation

- analysis of linear and nonlinear networks
- circuit modelling, computer aided network modelling
- solving of nonlinear differential equation systems by linearization methods and by numerical computing
- analysis of chaotic systems
- noise analysis of linear circuits
- control system design and analysis
- optical system modelling, design and evaluation
- literature survey
- computer aided data processing and visualisation
- low and high frequency circuit and system design

New scientific results of the theses

I. cluster of theses statements: Optoelectronic noise suppression for solid-state lasers

The optical generation of microwaves by using two-frequency solid-state lasers presents an efficient way of generating and transmitting high quality local oscillator signals in fibre-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 milimeter wave 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 (100kHz-2MHz).

In order to reduce this resonance term in the Relative Intensity Noise (RIN) spectrum, optoelectronic feedback loop can be used. A possible example of an LMDS head station containing mode locked and noise suppressed solid-state laser can be seen in Fig. 1.1.

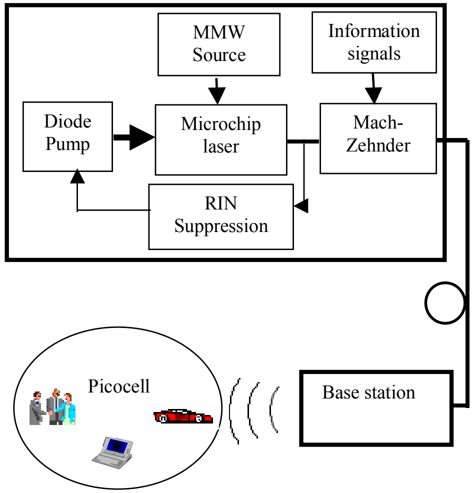

Fig. 1.1. Solid-state laser based optical-mobile system

Fig. 1.2. shows the intensity noise enhancement at the relaxation oscillation frequency of a $Nd:YVO_4$ microchip laser. The optical pump had a power of 100mW.

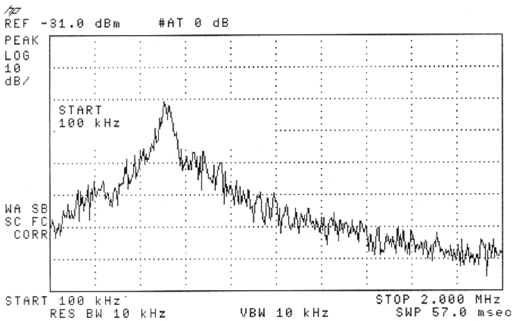

Fig. 1.2. $Nd:YVO_4$ laser intensity noise peak (relaxation oscillation frequency: 500kHz, optical pump power: 100mW).

T3/3: I have investigated the effect of the coherent filter transfer function on the phase-to-intensity conversion and on the possible noise suppression both for Unbalanced Mach-Zehnder Interferometer and for three tap transversal optical filter. Additionally I have explained in detail the formation process of the output intensity noise in different structures. Based on the comparison analysis taking into account the different operation points and working regimes I have developed a design support method for noise suppressing filters. ([Csörnyei, 2007e])

Exploitation of results

The results of the dissertation were published in Hungarian and international journals, conference proceedings and technical reports. Additionally some of these results were already moved into educational material. On the other hand I have got two independent citation.

Publications corresponding to the theses

Article in edited book

[Csörnyei,2003a] **M.Csörnyei,** T.Berceli, B.Klein: „Technology for mobile society", Editor: M. Muraszkiewicz, *MOST Mobile Open Society through Wireless Telecommunications press*, January, 2003. pp. 180-187. L

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Foreign language paper published in international conference proceedings

[Csörnyei,2000] **M.Csörnyei**., A.Zólomy, B.Klein: „Non-linear behaviour of low noise optical receivers", *3rd International Summer School, Interactions between Microwaves and Optics, OMW*, Grenoble, France, September 1-5, 2000.

It is now obvious that for narrow linewidth lasers significant noise suppressions is feasible in the coherent working regime. However it has to be paid attention to the location of the laser carrier on the filter transfer function. Driving the filter at the maximum point (out-of-quadrature point) a noise conversion with uniform decay can be observed (Fig. 3.4.). On the contrary positioning the optical carrier on the quadrature point the phase induced output intensity noise can have a 20dB higher level which makes the noise suppression for most of the lasers impossible.

I have carried out similar investigations for the coherent version of the three tap transversal filter too, with results analogous to the ones detailed here above.

As a further result I have explained in detail the reason of the here introduced effect of the coherent filter transfer function.

The result of the comparison analysis investigating the effect of the different operation points and different structures are summarized in the Table 3.1. This presents an easy to use design tool in engineering filters for optical noise suppression.

Table 3.1.

	Coherent	**Incoherent**
UMZI out-of-quadrature point	Narrow band periodic uppression (FP, DFB)	Narrow band periodic suppression (FP)
UMZI minimum	x	x
UMZI quadrature point	x	x
FIR out-of-quadrature point	Broad suppression (FP, DFB)	Broad suppression (FP)
FIR minimum	x	x
FIR quadrature point	x	x
FIR local maximum	Broad suppression (FP, DFB). Frequency shifted suppression points.	x

Letter x stands for combinations which are impossible or have too high noise conversion.

The new results in this field are summarized in the following statement:

As it is shown in Fig. 1.2. there is a 40dB noise enhancement at the laser relaxation oscillation close to the optical carrier. For the proper design of the noise suppressing optoelectronic feedback loop a simple mathematical model is required which fits to the laser transfer characteristics. According to the laser noise measurements the new model has a high resonance peak and 180° phase shift at the relaxation oscillation frequency. This model (1.1) is based on the measured parameters of the $Nd:YVO_4$ solid-state laser and makes the design of the noise suppression feedback loop easier.

$$G(s) = A_0 \frac{1}{\left(1+\frac{s}{\omega_{f1}}\right)\left(1+\frac{s}{\omega_{f2}}\right)} \qquad (1.1)$$

T1/1: I have developed a new noise model for designing optoelectronic feedback based noise suppression of solid-state lasers. By means of the new model the design and calculation of the noise suppression feedback loop was facilitated. ([Csörnyei, 2002a] [Csörnyei, 2002c], [Csörnyei, 2003b])

Using the newly introduced laser noise model I have realized an optoelectronic noise suppression feedback loop which is depicted in Fig. 1.3. The achieved noise suppression can be seen in Fig. 1.4.

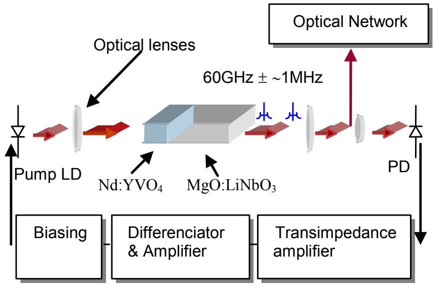

Fig. 1.3. Optoelectronic feedback loop in an optical transmitter containing $Nd:YVO_4$ laser.

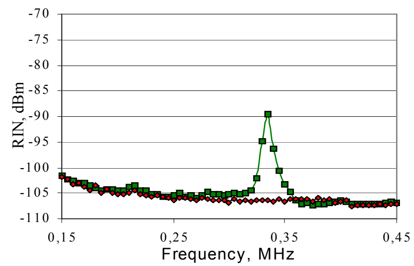

Fig. 1.4. The observed noise suppression at the relaxation oscillation frequency of the $Nd:YVO_4$ solid-state laser.

T1/2: In order to verify the applicability of the noise model I have designed an optoelectronic feedback loop for the noise suppression at the $Nd:YVO_4$ relaxation oscillation frequency. I have performed tentative measurements and confirmed a 17dB noise suppression. This noise suppression result allows of using this kind of lasers in optical-mobile telecommunication systems. ([Csörnyei, 2002a] [Csörnyei, 2002c], [Csörnyei, 2003b])

In order to be able to exactly identify the parameters of the newly introduced laser model I had to solve the rate-equations of the $Nd:YVO_4$ laser crystal. To do this first I have linearized the nonlinear nonautonomous differential equation system and then I have determined the conditions of stability. The stability analysis of the equation system was necessary for the later dynamic analysis of the laser structure.

T1/3: For determining the technical parameters of the noise model introduced in the theses statement of T1/1 I have linearized and solved the $Nd:YVO_4$ laser crystal's rate-equations which are presented by a nonlinear, autonomous differential equation system. This way I could determine the frequency, attenuation and time function of the relaxation oscillation which results are in good agreements with the measurements. By solving the rate-equations I have defined the conditions of stability as well. The information about stability was required for the subsequent dynamic analysis. ([Csörnyei, 2003g])

In addition I had the aim to determine the margin of the proper operation of the noise suppressing optoelectronic feedback loop. The first step in this analysis was the assume the by the photodiode detected and in the feedback loop amplified and phase shifted signal as a modulating signal of the pumping laser diode. Considering small modulation depth the loop works in normal operation and noise reduction is possible at the laser relaxation oscillation frequency. My goal was to declare the value of the maximal modulation depth at which normal noise suppression operation is still feasible. To pursue this analysis I have extended the rate-equations with a time dependent term describing the pump modulation effect of the feedback signal. The so modified rate-equations had to be handled like an nonautonomous nonlinear differential equation system. Subsequently I have numerical solved the equation system for different optical pumping rates and for different modulation depths in order to map the laser dynamic behaviour.

As a control first I have solved the equation system without feedback by numerical methods and I have ended up with the results depicted in Fig. 1.5-1.6. These figures are in good coincidence with the outcome of the previous calculations achieved by solving the linearized equations. It is shown that without feedback the laser operates with constant photon and population densities after a transient of the relaxation oscillation. Fig. 1.7. depicts these results in the phase portrait. Here can be seen that the solution in this case is a stable focus.

Increasing the amplitude and thus the modulation depth of the feedback signal the solution goes over first into a limit cycle (Fig. 1.8.). By further boosting the signal level the result of the equation system starts to make period doubling bifurcations (Fig. 1.9-1.10.) and later ends up in a chaotic state (Fig. 1.11-1.12.). All these calculations were done with an optical pump rate of 0.7.

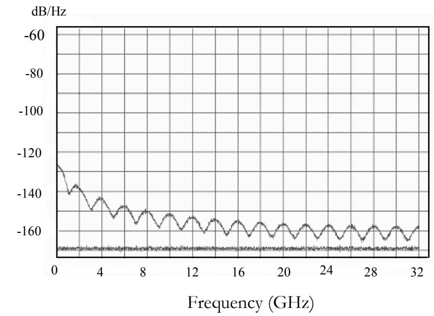

Fig. 3.2. Phase noise induced intensity noise at the output of 2MHz linewidth laser driven three tap optical filter (delay difference: 0.5ns, RIN=-170dB/Hz)

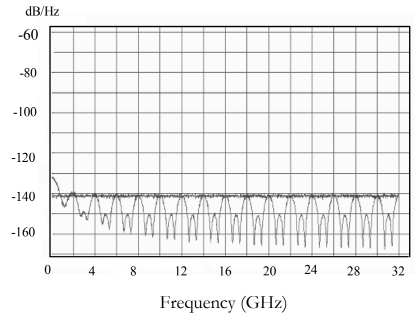

Fig. 3.3. Intensity noise reduction by a three tap filter. Above 3GHz the phase induced intensity noise is already smaller than the -140dB/Hz original laser noise level and thus at these frequencies periodic noise suppression is feasible. (laser linewidth: 2MHz)

T3/2: For optimizing the filter's noise suppression operation I have analyzed the phase-to-intensity noise conversion of the three tap optical transversal filter and I have got the solution in closed form. Additionally I have proofed both by calculations and simulation that despite the noise conversion this kind of structures present a good possibility for noise suppression and a noise reduction of 10dB is achievable. ([Csörnyei, 2007e])

Concerning the coherent transversal optical filters the shape and level of the output spectral density is highly depending on the frequency location of the optical carrier on the filter transfer function. Depending on the location of the carrier the definition of different operation points is possible.

Taking into account again the interferometer with 1ns delay difference. The simulated noise conversion having the optical carrier at the maximum point and at the quadrature point (-3dB) of the transfer function is depicted in Fig. 3.4. and 3.5. respectively.

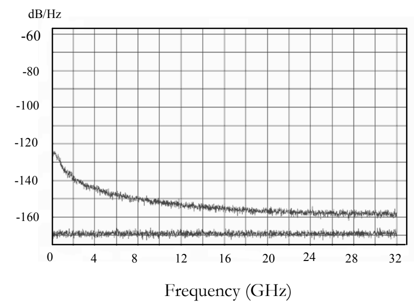

Fig. 3.4. Noise conversion having the laser carrier at the transfer function maximum.

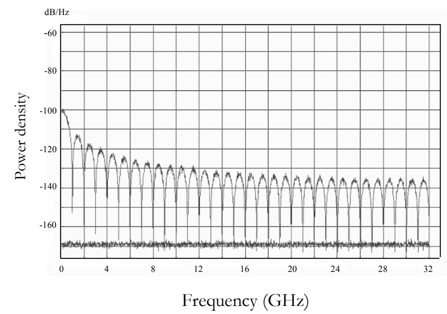

Fig. 3.5. Noise conversion having the laser carrier at the transfer function's –3dB point.

Similar to the case of the Unbalanced Mach-Zehnder Interferometer if one want to use transversal opto-microwave filters for laser intensity noise reduction the filter's phase-to-intensity noise conversion has to be analyzed in order to avoid the event when the filter itself is increasing the noise level of the optical source. This kind of calculations and investigations in the point of view of the noise reduction was first carried out in my publications.

T3/1: I have suggested optical-microwave transversal filters for noise suppression in case of semiconductor laser diodes. By this approach the noise suppression frequency band can be significantly extended compared to the one achievable by using Unbalanced Mach-Zehnder Interferometers. ([Csörnyei, 2005a])

Significantly extending the method applied in the second group of my theses statements I have foremost calculated the phase-to-intensity noise conversion in closed form for the case of three tap optical-microwave finite impulse response filters. This was done in order to support the design of such structures for noise filtering applications. The output power density was calculated by determining the Fourier-transformation of the autocorrelation function of the summation of the differently delayed output intensities. The graphical depiction of the calculation results can be seen in Fig. 3.1. for both a typical coherent (τ=0.5ns) and incoherent (τ=0.5μs) setup.

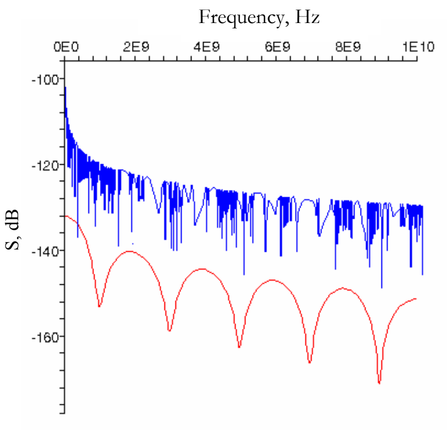

Fig. 3.1. The calculated output power density at the output of a three tap transversal optical filter induced by the input laser phase noise. (the filter coefficients present a uniform distribution, attenuation was neglected). The upper (blue) curve is for the incoherent case (τ=0.5μs), the lower (red) curve stands for a coherent setup (τ=0.5ns).

The calculations were verified by using the VPIphotonics™ optical simulation software. The simulated results for the three tap filter's phase-to-intensity noise conversion and for so achievable intensity noise suppression are depicted in Fig. 3.2-3.3.

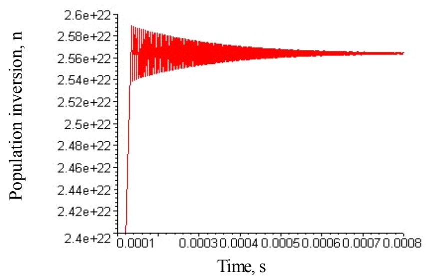

Fig. 1.5. Numeric result for the turn on transient of the population inversion density (pumping rate: W=0,7).

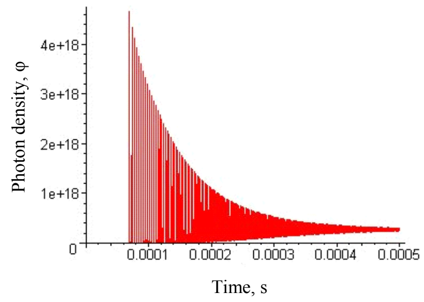

Fig. 1.6. Numeric result for the turn on transient of the photon density (pumping rate: W=0,7).

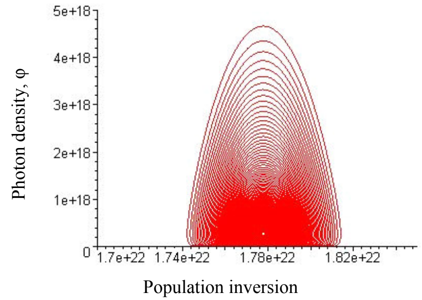

Fig. 1.7. Turn on transient of the autonomous system depicted in the phase portrait. The result is a stable focus. Calculated time domain: 0..0,009s.

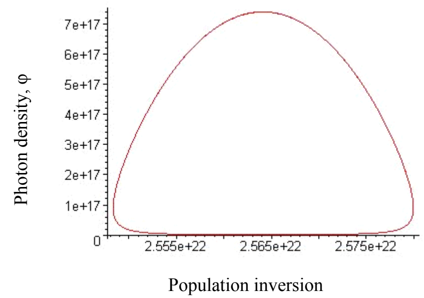

Fig. 1.8. Solution of the time variant nonautonomous rate equations at a modulation depth of 25%. The phase portrait depicts a limit cycle.

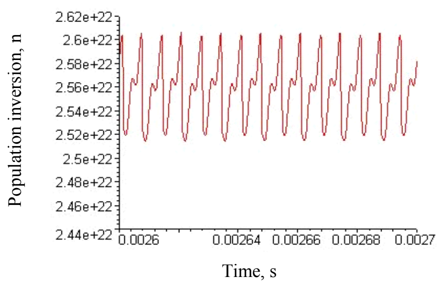

Fig. 1.9. Time variant solution for the population inversion density at a feedback modulation depth of 35%. The corresponding result for the photon density is a similar period doubling bifurcation.

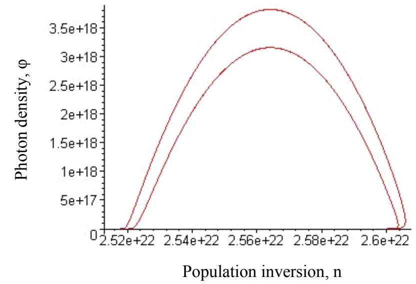

Fig. 1.10. Solution of the time variant nonautonomous rate equations at a modulation depth of 35%. The phase portrait depicts the first period doubling bifurcation.

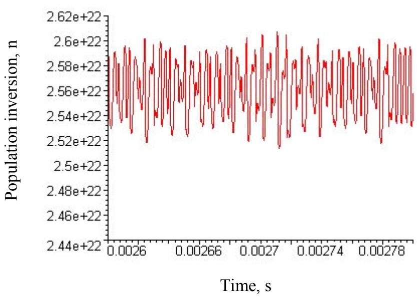

Fig. 1.11. Chaotic solution for the population inversion at a modulation depth of m=94%.

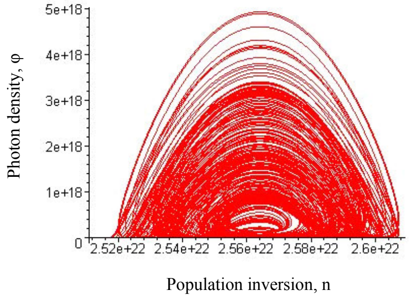

Fig. 1.12. Phase portrait of the chaotic solution (m=94%).

T1/4: I have recognised and confirmed that in case of solid-state lasers the optoelectronic noise suppression signal can act as a pump modulation and thus it can strongly influence the laser's dynamic behaviour. In order to map the dynamic operation of the laser I have numerically solved the pump modulated rate equations presented by a nonautonomous nonlinear differential equation system. Solving the system for different modulation depth values I have determined the way of photon density and population inversion density trough a sequence of bifurcations to the chaos. ([Csörnyei, 2007b], [Csörnyei, 2007d])

The bifurcation diagram of the photon density is depicted in Fig. 1.13.

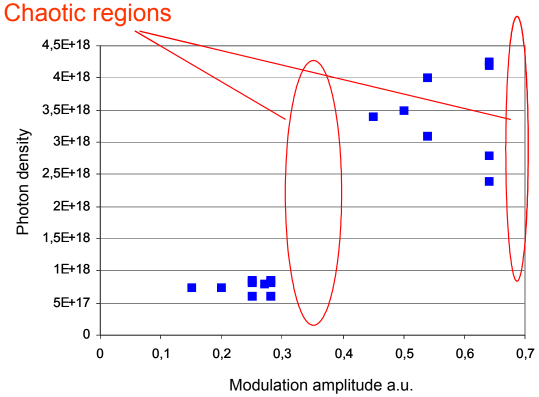

Fig. 1.13. Bifurcation diagram of a Nd:YVO_4 laser.

T2/2: I have determined a general limiting estimation for the delay difference of noise suppressing interferometers, in case of Fabry-Perot and DFB lasers. ([Csörnyei, 2007a])

In case of optical-microwave interferometer based noise suppression there is a further question concerning the use of coherent or incoherent structures. Realization of incoherent structures is easier due to its robustness against temperature and polarization changes, however application of this kind of systems is not always possible due to the stronger noise conversion compared to the coherent systems.

Based on my calculations presented so far, and on the results published in the literature [Armstrong, 1966], [Moslehi, 1986], [Capmany, 2000] I can state that the realization of noise suppression interferometers is much easier in the incoherent regime, however the phase-to-intensity noise conversion can have a 20-30dB higher level compared to the coherent solutions.

Based on my previous calculations it is obvious that the decision between coherent and incoherent systems can only be made depending on the chosen laser.

In case of DFB lasers, due to their quite low relative intensity noise (<-135dB/Hz) I can state that the only way for noise suppression is presented by coherent structures. Otherwise the noise contribution of the noise suppressing system were higher than the original noise of the laser.

Concerning Fabry-Perot laser diodes, the maximal level of the RIN at the relaxation oscillation frequency is typically less than -110dB/Hz, which means that both coherent and incoherent approach is feasible.

T2/3: I have recognized that in case of DFB laser diodes only coherent structure can be used for noise suppression, however for Fabry-Perot lasers both coherent and incoherent schemes can be applied. ([Csörnyei, 2007a])

III. cluster of theses statements: Noise suppression of semiconductor laser diodes by transversal opto-microwave filters

In this theses statement I have suggested optical transversal filters for noise suppression. For defining the conditions of the proper operation the analysis of the phase-to-intensity noise conversion was necessary in this case also. Using this calculation I could present quantitatively the possible noise suppression.

T2/1: I have tentatively proofed that the Unbalanced Mach-Zehnder Interferometer presents a possible way for laser diode noise suppression and thus it can be used in short haul subcarrier multiplexed optical transmission systems.

In order to optimize the operation I have analyzed the phase-to-intensity noise conversion of the structure in detail, assuming both phase noise and white amplitude noise at the input. I have determined the output spectral density in a closed form. The calculations were proofed by computer aided simulations and labour measurements.

Additionally I have showed that the calculation results can be adopted assuming band limited white noise as an amplitude noise at the input of the interferometer. ([Csörnyei, 2005b], [Csörnyei, 2005f], [Csörnyei, 2006b], [Csörnyei, 2007a])

Using the results of T2/1 I have calculated the output intensity noise for a couple of combinations of typical laser linewidth and interferometer delay difference values. The numbers I have got are presented in Fig. 2.6. Comparing these results with the typical relative intensity noise (RIN) levels of FP and DFB lasers I could give a limiting estimation for the time delay difference of the to be designed UMZI based noise suppression structure.

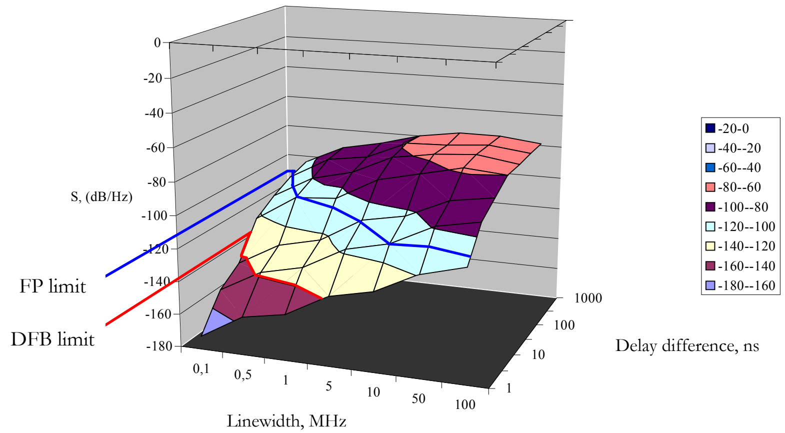

Fig. 2.6. Phase noise induced intensity noise at the UMZI output in case of different laser linewidth and interferometer delay difference value. The presented output power levels are valid at 0Hz off the optical carrier. Additionally I have marked the typical RIN levels for FP and DFB lasers (RIN_{FP}≈-110dB/Hz, RIN_{DFB}≈-140dB/Hz). In case of typical RIN levels noise suppression is possible at parameter combinations lying left from the limit line.

NOISE SUPPRESSION RESULTS OF TELECOMMUNICATION LASERS Csörnyei Márk, Ph.D. thesis statements

The result of my computational experimentation was, that tuning the feedback amplitude and thus the feedback modulation depth the solution starts to go through period doubling bifurcations and ends up in chaotic oscillations.

The chaotic signal which I have observed has no periodicity and fits to all the requirements of a chaotic solution [Tél, 2002], [Gleick, 1999].

One of the results of my numerical experimentation is that in case of microchip Nd:YVO_4 solid-state laser the bifurcation of the solutions starts already at a low modulation depth of 35%. Looking the results reported in the literature the typical modulation depth value at which the first bifurcations appear is 80% [Luo, 1998], [Klische, 1984], [Arecchi,1982].

After determining the maximal limit for the modulation depth without bifurcation and chaotic oscillations, the maximal feedback loop amplification can be now calculated, and the chaos free feedback loop design is supported.

T1/5: By solving the nonautonomous rate-equation system I have showed that in case of Nd:YVO_4 the first period doubling bifurcations appear at a modulation depth of 35%. Thus I have given a margin for the maximal modulation depth realized by the feedback loop. According to the calculation results I can state that the modulation depth value causing normal noise suppression and the one resulting in chaotic oscillations are the same order of magnitude. This means that the dynamic analysis of the system is necessary in order to avoid chaotic oscillations during noise suppressing.

These are the first results dealing with possible chaotic behaviour in case of noise suppressed solid-state lasers. ([Csörnyei, 2007d])

II. cluster of theses statements: Unbalanced Mach-Zehnder Interferometer based noise reduction for semiconductor lasers

I have tentatively proofed that the Unbalanced Mach-Zehnder Interferometer (UMZI) structure (Fig. 2.1.) can be used for noise suppression in the case of semiconductor laser diodes. In order to be able to optimize this kind of operation I have analyzed the phase-to-intensity noise conversion of the UMZI structure. Among others I have extended the results of [Armstrong, 1966] and [Salehi, 2006]. The referenced publications assume an interferometer input signal loaded only with phase noise and they neglect the effect of the input intensity noise. In my calculations both the phase noise and the intensity noise was taken into account and thus I could get a more realistic result for the output power spectrum of the Unbalanced Mach-Zehnder Interferometer.

I have analyzed the phase-to-intensity noise conversion for intensity noise originating in white noise and in band limited white noise as well.

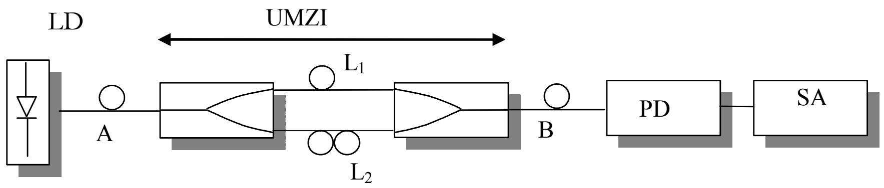

Fig. 2.1. Unbalanced Mach-Zehnder Interferometer (UMZI) depicted between A and B. In this measurement setup the output signal of the laser diode (LD) is passing through the UMZI. The output is detected by a photodiode (PD) and further processed by a spectrum analyzer (SA).

One of the most important results of my calculations is the exactly determined output power spectrum of the Unbalanced Mach-Zehnder Interferometer assuming both intensity and phase noise at its input. By this calculation a more detailed and correct description is given about the noise conversion characteristics of the interferometer. In the following formula for the output spectral density δ is for the laser linewidth, σ is the standard deviation of the noise processes and τ is the time delay difference between the arms of the interferometer.

$$S_i = 2\pi\delta_D(\omega)\left\{\frac{1}{4}+\frac{1}{2}\sigma_\xi^2+\frac{1}{4}\sigma_\xi^4+\left[\frac{1}{2}+\frac{1}{2}\sigma_\xi^2\right]\exp\left(-\frac{1}{2}\delta\tau\right)+\frac{1}{4}\exp(-\delta\tau)\right\}+\frac{1}{2}\sigma_\xi^4+\frac{1}{2}\sigma_\xi^4\cos(\omega\tau)+$$
$$\frac{\exp(-\delta\tau)}{\delta}\left(\frac{(2\pi f/\delta)\sin(2\tau\pi f)+\sinh(\delta\tau)}{1+(2\pi f/\delta)^2}-\frac{\sin\left(2\pi f/_\delta\,.\delta\tau\right)}{2\pi f/_\delta}\right)+\left[2\sigma_\xi^2+2\sigma_\xi^2\cos(\omega\tau)\right]\frac{\exp(-\delta\tau)}{\delta}\frac{(2\pi f/\delta)\sin(2\tau\pi f)+\sinh(\delta\tau)}{1+(2\pi f/\delta)^2}$$

In my calculations I was the first defining the exact proportion of phase noise induced and intensity noise induced noise terms in the output spectral density. In addition I have showed that assuming band limited white noise as an input amplitude noise process the result calculated for the case of white noise can be easily adopted.

Based on the calculation results shown above it was possible to develop a new design method for noise suppressing Unbalanced Mach-Zehnder Interferometers taking into account the phase-to-intensity noise conversion of the noise suppressing structure itself. In order to be able to use a system for noise reduction I had to calculate its own noise conversion. This way of design was introduced first in my publications.

Investigation of phase-to-intensity noise and intensity-to-intensity noise conversion is highly important if one want to use this kind of structure for noise suppression. Avoiding this analysis the interferometer intended for noise suppression can act as a main noise contributor.

In order to support the design of UMZI for noise reduction I have depicted the output spectral density of these structures for typical coherent and incoherent situations in Fig. 2.2 and 2.3. Using this figures one can decide if the selected interferometer can be used for noise suppression or not.

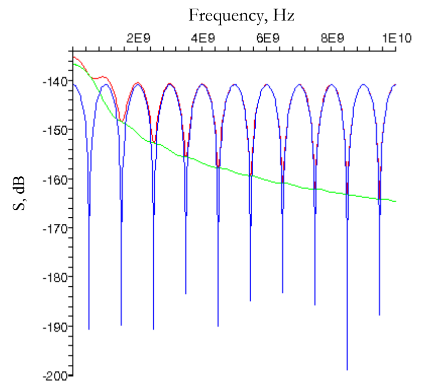

Fig. 2.2. Output spectral density in case of 2MHz linewidth DFB (Distributed Feed-back Laser) laser (RIN=-140dB/Hz) and 1ns delay difference UMZI. Blue curve: intensity noise induced output intensity, green curve: phase noise induced intensity noise, red curve: resultant noise level.

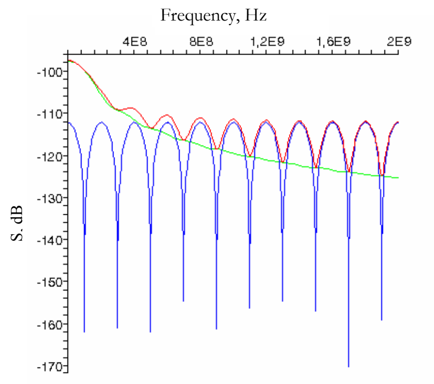

Fig. 2.3. Output spectral density in case of 20MHz linewidth Fabry-Perot laser diode (RIN=-110dB/Hz) and 5ns delay difference UMZI. Blue curve: intensity noise induced output intensity, green curve: phase noise induced intensity noise, red curve: resultant noise level.

As it is shown in the above figures my calculations can be used for exact determining of the possible suppression frequencies at selected laser linewidth and interferometer delay difference values. It can be also seen in these figures that if the phase noise induced output intensity noise is smaller than the laser intensity noise a periodic noise suppression will be feasible. Usually this kind of operation is only possible at frequencies higher than the limit frequency.

Furthermore it is very important to note the significant difference in converted noise power of coherent and incoherent structures.

For the verification of the calculation results I have carried out computer simulations (Fig. 2.4.) and tentative measurements (Fig. 2.5.). There is a good coincidence between the calculated and measured results of Fig. 2.3. and 2.5..

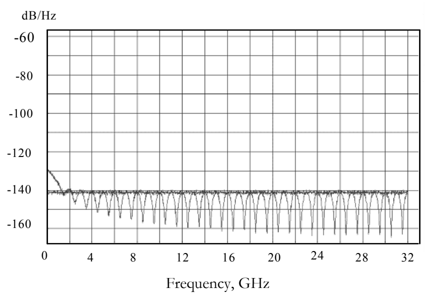

Fig. 2.4. Simulation (VPIphotonics™ simulator) for verifying the calculation results shown in Fig. 2.2.

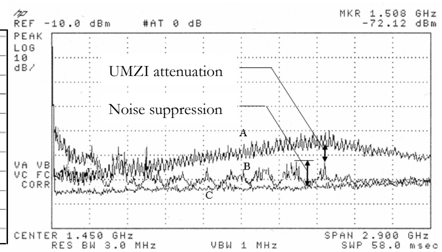

Fig. 2.5. Measured noise suppression A) FP laser RIN. B) UMZI noise suppression C) noise floor or the measurement setup.