Fiber-delay lines for intensity noise suppression in optical links

MÁRK CSÖRNYEI, TIBOR BERCELI

Budapest University of Technology and Economics,
Department of Broadband Infocommunication and Electromagnetic Theory

{csornyei, berceli}@mht.bme.hu

Reviewed

Key words: semiconductor lasers, intensity noise, optical-microwave filtering, noise suppression, coherence

In case of short haul optical links, optical local area networks or optical-mobile networks the most important noise source is the relative intensity noise (RIN) of the laser diodes. This paper will report on a new all-optical technique of intensity noise suppression for 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 in the microwave domain and thus improve the link signal-to-noise ratio. Extending the UMZI to fiber-delay line filter the noise reduction capability can be further increased. Additionally the condition of stable, incoherent operation is detailed.

1. Introduction

The increasing demand for new telecommunication applications and higher data rates requires continuous research concerning the technical parameters of the state-of-the art optical networks. In addition the optical signal processing solutions need further improvement in the characteristics of photonic devices as well.

One of these most important physical parameters of the optical link is the *Relative Intensity Noise (RIN)* of laser sources, which has major influence on the detected signal-to-noise ratio especially in short haul optical transmission.

The spectral density of the RIN is not equally flat around the optical carrier. It has a remarkable increment at the relaxation oscillation frequency which is defined by the laser internal operation. In case of laser diodes the relaxation oscillation frequency, in connection with the intensity noise maximum overlaps with the modulation information in the microwave band, which causes a quality degradation in the signal transmission. It is now obvious that in future high transmission capacity optical networks the intensity noise suppression is a crucial problem.

Before revising the various possible ways of RIN suppression it is worth to dealing with the causing effects of the intensity noise themselves. The main reasons are typically the temperature fluctuations, the spontaneous emission of the laser sources and the optical reflections caused by the refractive index changes at light coupling into fibers or other optical devices.

To cancel the intensity noise originating in optical reflections optical isolators can provide an appropriate solution. In this case the reflected signal parts are significantly attenuated and can not contribute to developing the intensity noise. Optical isolators present a right possibility for noise suppression but only in cases where the RIN is mostly generated by coupling reflections.

In order to optimize the signal-to-noise ratio there is a further opportunity in carefully adjusting the laser diode biasing. Increasing the bias current the relaxation oscillation of the laser diode shifts to higher frequencies with a smaller resonance amplitude, which means a decrease of the intensity noise maximum. Properly setting the bias current the noise enhancement can be moved out of the selected transmission band and suppressed. This way of noise cancellation is useful only in case of narrow band modulation. The further drawback of this solution goes back on the fixed value of the bias current, which is why the source output power cannot be adjusted freely and we lose on flexibility of the network. Adding or removing nodes of the optical network should influence the output laser power which is impossible if the biasing is kept constant to reduce the intensity noise.

For intensity fluctuation suppression of solid-state lasers the optical feedbacking of the laser crystal output power means a well known and efficient way [1,2]. With the design of an optoelectronic control loop remarkable suppression can be achieved at the frequency of the relaxation oscillations. This method can be very well used for the high peak of the low frequency (<10MHz), narrow band intensity noise of solid-state lasers, but in case of the high frequency (>1GHz), broadband noise increment of laser diodes it is unusable.

The *Unbalanced Mach-Zehnder Interferometer (UMZI)* presents a uniform solution for noise suppression both for laser diodes and solid-state lasers (Nd:YAG, Nd:YVO_4) [3]. This approach, which is dealt with in this paper, has more advantages than the ones mentioned so far. The UMZI based intensity noise cancellation exclusively utilizes passive optical devices therefore it sports all the advantages of optical signal processing, i.e. insusceptible to electromagnetic interferences (EMI), it does not need electrical biasing and in comparison with copper based electronic systems it can be realized in smaller sizes and from the more economical SiO_2.

The structure of the paper is as follows. Section 2 accounts for the fact that intensity noise suppression of different laser sources is unbearable. Section 3 illustrates in detail the operation of the unbalanced (asymmetric) Mach-Zehnder interferometer in an intensity noise suppression application, the measurement results and the comparison of coherent and incoherent working regime. Section 4 summarizes the results so far and further possible efforts in this field.

2. Noises of optical transmissions

In case of intensity modulated optical transmission using PIN photodetector the transmission noise comprises three terms, which are the shot noise, the receiver thermal noise and the relative intensity noise of the laser source [4]. Supposing independent noise sources, the following signal-to-noise ratio can be formulated at the output of the photodetector

$$\frac{S}{N}=\frac{I^2}{\sigma_s^2+\sigma_t^2+\sigma_R^2} \quad (1)$$

In the numerator of (1) there is the square of the photodetector current while in the denominator there is the variance of the noise source currents. The variance of the three noise components are expressed in (2-4):

$$\sigma_s^2=2eB(I_p+I_d) \quad (2)$$

$$\sigma_t^2=4k_BT_0B/R_L \quad (3)$$

$$\sigma_R^2=\frac{\eta^2e^2}{(hf)^2}(RIN)P^2B \quad (4)$$

In the formulas of (2-4) e stands for the charge of the electron, k_B for the Boltzmann-constant, B for the bandwidth of the photoreceiver, P for the optical power, η for the quantum efficiency, h for the Planc-constant, I_p for the photocurrent and I_d for the dark current. RIN gives the level of the relative intensity noise to the optical carrier. It is obvious that both the level of the shot noise and the intensity noise depend on the value of the incoming optical power, while the thermal noise is only dependent on the receiver temperature and its load resistor.

When substituting the typical parameters of the optical links of today operating in the 1550-nm band for the equations (2-4), the relative intensity noise can oversize the impact of the thermal noise based upon the -130, -150 dB/Hz RIN values typical of *Fabry-Perot (FP)* lasers. However, as the value of (4) decreases by increasing the transmission length and the link attenuation, over certain fiber lengths and network sizes the component deriving from intensity noise sinks bellow the thermal noise of the receiver, therefore its impact will be irrelevant.

It is clear that the RIN level and the noise suppression methods aiming at the amplitude fluctuation are most relevant in case of short haul optical transmissions, optical-mobile systems and optical *LMDS-s (Local Multipoint Distribution System)*. On the basis of calculations of [5] the relative intensity noise is the determining noise source of optical links up to about 30 km length.

From these facts it emerges that further improvement of the quality of local and urban optical network transmissions is only feasible by using RIN noise reduction methods.

3. Interferometer in noise suppression application

The Unbalanced Mach-Zehnder Interferometer based intensity noise suppression scheme for laser diodes is depicted in *Figure 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.

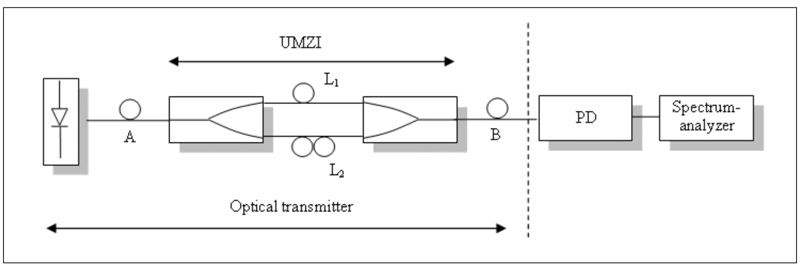
In that structure we have utilized an InGaAsP *Multi-Quantum Well (MQW)* Fabry-Perot (FP) laser diode. The output power was 0.1-2 mW. The pigtailed output of the laser diode was connected to the interferometer, which consisted of two Kamaxoptic 3 dB (50/50) splitter modules and two SMF-28 type single mode optical fiber in-between.

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 (5) an UMZI path length difference of 0.05 m is required in order to reduce the noise at 2 GHz [6].

$$\tau=T_2-T_1=\frac{n}{c}(L_2-L_1)=\frac{1}{FSR}\Rightarrow\Delta L=\frac{c}{n}\cdot 250\,ps=5cm \quad (5)$$

In (5) n stands for the fiber effective refractive index, c is velocity of light in vacuum, L_1,L_2 and T_1,T_2 are the UMZI arm lengths and the delays respectively. Based on the delay difference the *Free Spectral Range (FSR)* of the interferometer can be calculated, which gives the frequency difference of the periodic suppressions in the transmission function. In the case of a 5 cm length difference the FSR is 4 GHz as it is depicted in *Figure 2.*

Figure 1. Unbalanced Mach-Zehnder Interferometer for intensity noise suppression of laser diodes.



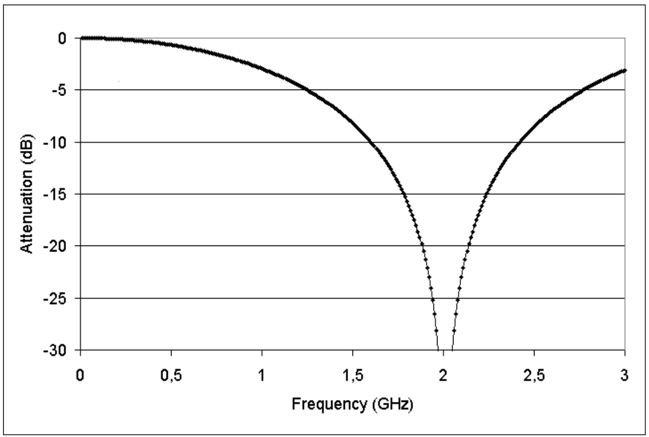


Figure 2. UMZI transfer function. (FSR = 4 GHz, ΔL= 5 cm)

Since the by the 5 cm fiber length difference defined 250 ps delay difference is much shorter than the coherence time of the laser source the proposed interferometer works in the strong coherent regime. The coherence time of the our FP laser diode is 3 ns which can be calculated by (6) from the laser spectral linewidth ($\Delta\nu$=100 MHz).

$$\tau_c = \frac{1}{\pi\Delta\nu} \tag{6}$$

During coherent operation it is not the desired intensity-based summery that occurs at the interferometer output but the basis of the interference is the field intensity spreading in the fiber [7]. Formulating it in another way, while the interferometer in the incoherent working regime can be regarded as a linear network concerning optical intensity and the interference only influences the envelope realized by intensity modulation, in the coherent case the optical carrier can fall prey to interference [8].

In the coherent case, i.e. if the difference in the arm length of the interferometer acting as a filter is less than the coherence length of the laser ($\tau<\tau_c$), the transmission function becomes extremely sensitive and instable since the output signal appears or disappears accidentally because of the interference also touching the carrier. While owing to very little differences in the interferometer arm lengths it is wearisome to maintain appropriate operation in the coherent regime, which is only possible by constantly supervising the optical phase and the system temperature and adjusting the biasing of the laser source very accurately, in case of larger differences in the fiber lengths and less FSR the noise reduction has to be realized in the incoherent regime.

In order to ensure the incoherent operation a fiber interferometer with a Free Spectral Range of 200 MHz (path length difference (ΔL): 1 m, n=1.5) was chosen instead because of its longer delay differences and stable incoherent operation. The noise suppression feasible with this structure is shown in *Figure 3.* and *Figure 4.* show the measured transfer function of the interferometer discussed above and the achieved noise reduction respectively. 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 Figure 4. The further suppression is possible at the selected frequencies but the measurement is limited due to the spectrum analyzer noise floor.

Actually the UMZI is an optical *FIR (Finite Impulse Response)* 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. Using UMZI, noise reduction is only possible at selected resonance frequencies of the interferometer *(Figure 5)*.

Figure 3.
UMZI with a Free Spectral Range of 200 MHz.
The measurement was done between the points of A and B of the structure depicted in Fig.1.
The interferometer has an attenuation of 6 dB and a noise suppression capacity of 15 dB at the selected resonance frequencies.

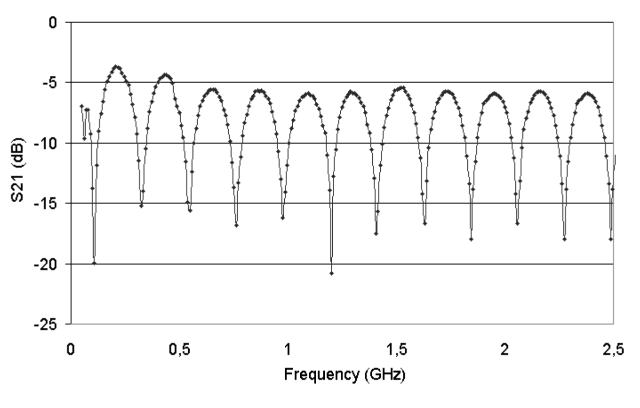
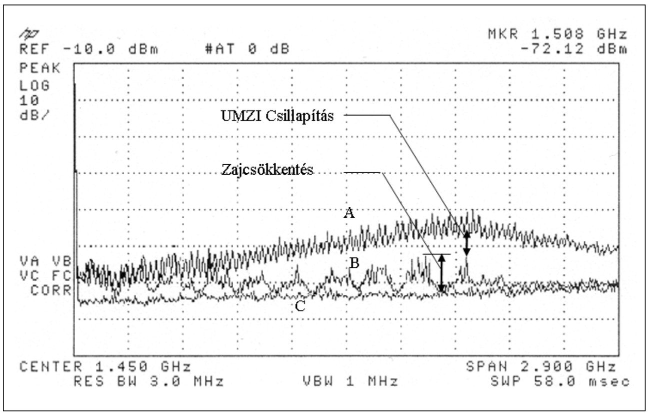


Figure 4.
Measured noise suppression of the UMZI structure of Fig.1.
A) Relative Intensity Noise of the investigated FP laser diode at 2 GHz.
B) Noise suppression realized by the interferometer.
C) Noise floor of the measurement setup.
Measurement conditions: ResBW = 3 MHz, No Video Averaging, Input Attenuation = 0 dB.



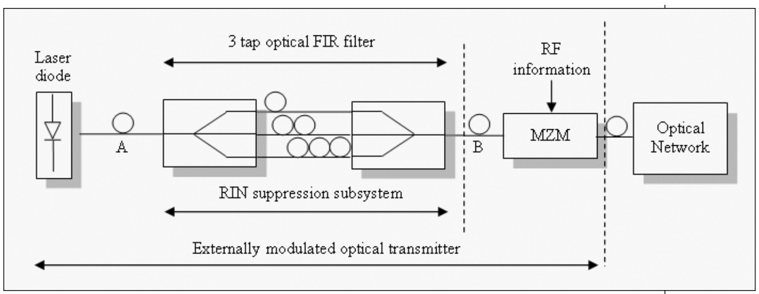


Figure 5.
3 tap optical transversal filter for laser diode noise cancellation. After the noise suppression blocks the information can be modulated with an external optical filter.

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. During the design of the optical transversal filter it is very important to fulfill the conditions of the incoherent operation, which means in our case that all the fiber length differences should be longer than the laser source coherence length.

Formulating the same in the frequency domain means, that in order to achieve a noise suppression at 2 GHz the interferometer with a FSR of 4 GHz should be replaced by an optical-microwave filter with a transfer function consisted of many narrower FSR-s. Taking into account these requirements concerning coherence we will end up with slightly different design methodology than in the case of commercial optical-microwave filters [8].

For calculation of the interferometer suppression frequencies (f_0) the well known [7] formula of (7) can be used.

$$f_0 = (2k+1)\frac{c}{2n_{eff}\Delta L} = \frac{2k+1}{2\Delta T} \qquad (7)$$

According to (7) for a RIN suppression at 2 GHz a FSR of 4 GHz is required which gives a delay difference of 250 ps (k=0). Intending to realize incoherent operation it is worth to setting the value of the constant k higher. Using k=11 and forcing f_0 to be 2 GHz a delay difference of 5750 ps will work out.

Using delay differences bigger than the 3 ns coherence time the transmission functions of *Figure 6.* and *Figure 7.* are feasible. Evaluating the structure of Figure 6. the noise suppression of *Figure 8.* can be achieved, where the noise cancellation band is pushed up to 400 MHz.

4. Conclusions

In our paper we have suggested passive all-optical solution for the suppression of relative intensity noise of local optical networks. We have looked into and presented the noise suppression that can be obtained by the asymmetric Mach-Zehnder interferometer. For widening the suppression band and securing stable incoherent operation we have introduced novel ideas that differ from the traditional filter design concepts.

Our results perfectly fit into the future concepts of fiber systems using only optical devices while lacking electronical signal processing elements.

Further objectives of our research are to analyze the impact of laser phase noise as well as to supervise the possibilities of the integrated optical implementation.

Acknowledgment

The authors acknowledge the Grant of the "National Research Foundation" (OTKA) No. T042557 and the European project Gandalf IST-1-507781-STP.

Figure 6.
Transfer function of the 3 tap incoherent optical transversal filter of Fig.5. The delay differences are: 3.25ns and 5ns. Coherence time: 3ns.

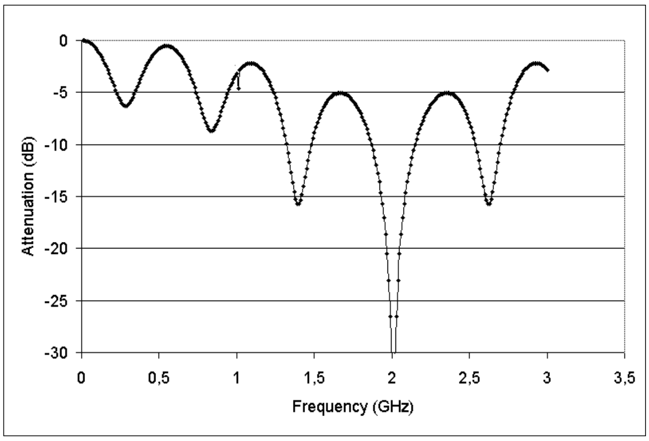
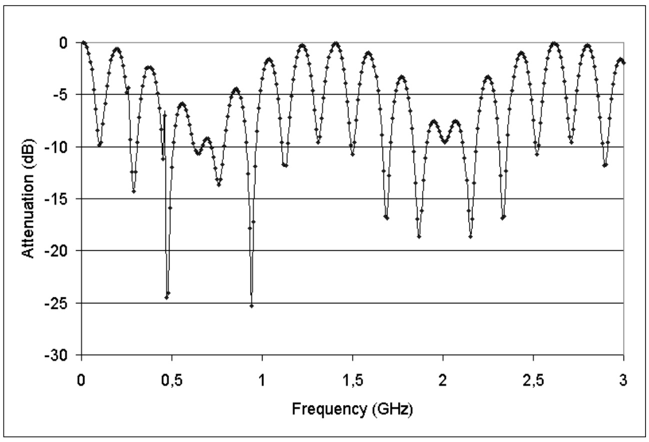


Figure 7.
Transfer function of the 3 tap incoherent optical transversal filter of Fig.5. The delay differences are: 5.75 ns and 5 ns. Coherence time: 3 ns.



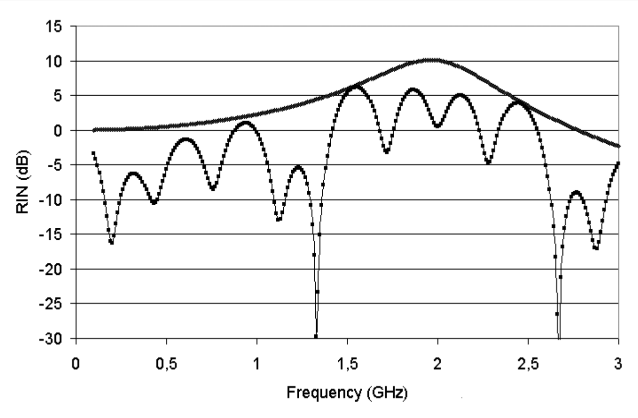


Figure 8.
Calculated noise suppression results based on the filter transfer function of Fig.6. Solid line: the calculated relative intensity noise of the investigated Fabry-Perot laser diode. There is a noise suppression of 10 dB in the range of the 2 GHz relaxation oscillation.

References

[1] T. J. Kane, "Intensity noise in diode-pumped single-frequency Nd:YAG lasers and its control by electronic feedback", IEEE Photon. Techn. Letters, Vol. 2, No.4, 1990. április

[2] M. Csörnyei, T. Berceli, P. R. Herczfeld, "Noise suppression of Nd:YVO4 solid-state lasers for telecommunication applications", J. Lightw. Techn., Vol. 21, No.12, pp.2983–2988. 2003. december

[3] M. Csörnyei, T. Berceli, T. Marozsák, "All-optical intensity noise suppression of solid-state lasers for optical generation of microwaves", XV International Conference on Microwaves, Radar and Wireless Communications, MIKON-2004, Varsó, Lengyelország, pp.781–784. 2004. május

[4] Frigyes I., "Hírközlő rendszerek", Műegyetemi Kiadó, 1998.

[5] Marozsák T. "Félvezető lézerek alkalmazása és modellezése segédvivős optikai rendszerekben", Doktori értekezés – BME, Budapest, 2004.

[6] B. Cabon, V. Girod, G. Maury, "Optical generation of microwave functions", Proc. OMW2000 Summer School, Autrans, France, 2000. szeptember

[7] A. Hilt, "Basics of microwave network analysis of optical circuits", Optical/Wireless Workshop in the framework of the European MOIKIT project, Budapest, 2001. március

[8] J. Capmany, "Fiber-optic filters for RF signal processing", Proc. OMW2000 Summer School, Autrans, France, 2000. szeptember

News

The Enhanced Long Distance Services Solution works together with Veraz Switching family and provides revenue streams for both carrier networks at any point in their transition from TDM to IP. Based on Veraz's programmable service engine, the LD services are easily customizable by the carrier or by 3rd parties.

The following the services available:

– Account Codes
– Number Translations (Toll Free)
– Personal Toll Free
– Security Toll Free
– Unauthorized User Redirect
– Tariff Announcements
– Pre-Subscribed International Long Distance
– Automated Collect Call
– Hotel PBX Billing

These services created from service building blocks (SBBs) utilizing XML scripted service logic and a politic engine. Enabling the rapid design, development, customization and network-wide deployment of new services.

Genesys Telecommunications Laboratories and Veraz Networks have new options for connecting enhanced customer interaction and contact center applications existing network resources.

The integration of Genesys Voice services platform, with the Veraz ControlSwich softswitch allows service providers to connect IP-based customer interaction and contact center applications with existing Public Switched Telephone Network (PSTN) interfaces, using Primary Rate Interface (PRI) and SS7 ISDN User Part (ISUP). This pre-defined connection decreases costs and supports faster deployment of enhanced services for enterprises, including hosted call center applications. Using Veraz Control Switch for management and switching of traffic among different networks helps carriers provide the same set of applications through different networks.

ITU hold a workshop on next generation networks (NGN) together with the Internet Engineering Task Force (IETF) in Geneva.

Since May 2004 intense work has taken place in ITU, towards the development of standards that will define services, network and systems architecture in he next generation of IP enabled communication systems, or next generation networks (NGN). The objectives of the workshop are to report the progress of ITU's work on NGN and explore specific issues that impact both the ITU and the IETF in order to better understand the work underway in the two organizations and to identify areas where action can be taken to make further progress.