REPORT DOCUMENTATION PAGE

Form Approved
OMB No: 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 26/11/2002

2. REPORT DATE TYPE Final technical

3. DATES COVERED *(From - To)*: 01-APR-2001 to 30-SEP-2002

4. TITLE AND SUBTITLE

High capacity hybrid fiber optic/wireless communications system

5a. CONTRACT NUMBER

5b. GRANT NUMBER

N00014-01-1-0680

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

01PR07589-00

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

Tibor Berceli, István Frigyes, Tamás Bánky, Márk Csörnyei, Attila Kovács, Eszter Udvary

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Technical University of Budapest
1111 Budapest, Goldmann György tér 3.
Hungary

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA, 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

ONR

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for Public Release, distribution is Unlimited

13. SUPPLEMENTARY NOTES

-

14. ABSTRACT

See attached paper

15. SUBJECT TERMS

Mode-locked laser stabilization. Noise peak suppression in microchip lasers.
16 QAM modulation of a subcarrier for optical systems.

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPONE NUMBER (Include area code)
U	U	U	UU	19	Berceli, Tibor / +36-1-463-2804

Standard Form 298 (Rev. 8-98)

20030320 007

High Capacity Hybrid Fiber-Optic/Wireless Communications System

Abstract

The microchip laser is a good candidate for producing a low noise optical beam. As the microchip laser works with locked modes, it is suitable for the optical generation of microwave or millimeter wave signals. However, the frequency difference between the two modes is not stable enough and therefore the generated signal will be unstable as well.

We developed a new approach for the stabilization of the relative frequency difference between the modes. For that purpose a high stability millimeter wave oscillator was designed and constructed utilizing dielectric disc resonators. The signal of the stable oscillator was injected into the laser resonator providing this way a stable difference frequency for the optical generation of microwave signals.

However, there is another problem because the microchip laser has a noise peak in the transmission band. We developed a new method to suppress that noise peak. The new method was verified by both simulations and measurements.

An experimental set-up was also built. It contained a high-power diode laser pumping a mode locked crystal laser. The frequency difference between the modes was around 20 GHz. After fiber transmission a 20 GHz signal was generated at the reception side by detecting the optical signal having two modes. About 15 dB noise suppression was achieved in the experiments.

New modulation methods were theoretically investigated to reduce the bandwidth requirement in combined optical-wireless systems. First of all, the 16 QAM modulation of a subcarrier proved to be a proper new approach.

FINAL REPORT

on the

„High Capacity Hybrid Fiber-Optic/Wireless Communications System"

- project

Authors:

Tibor Berceli, István Frigyes,
Tamás Bánky, Márk Csörnyei,
Attila Kovács, Eszter Udvary

Technical University of Budapest
Hungary

December 2002

MAIN GOALS OF THE RESEARCH

The aim of the proposed work was to support the existing ONR project called „Hybrid fiber optic/wireless system for high capacity military communication" by performing research on system problems considering the multipoint-to-multipoint applications, as well as investigations on different types of modulation methods and noise reduction approaches.

The Technical University of Budapest, Microwave Telecommunications Department carried out the following studies:

I. network studies related to hybrid fiber-optic wireless communications
II. reduction of the noise in the millimeter wave optical transmitter
III. RIN peak suppression of microchip lasers

The current hybrid fiber optic/wireless communication system distributes the information signals to dispersed wireless picocells in the optical domain. An efficient network must be developed that can accommodate multiple users within a single picocell, minimize interference between adjacent picocells and provide with seamless hand-overs between picocells. This task includes the theoretical and experimental analysis of the performance of multi-access/multicell schemes such as frequency re-use, FDMA, TDMA, CDMA and WDM. Channel impulse response measurements together with the transmitted multimedia characteristics had to be used to determine the appropriate wireless modulation and coding selections. Performance issues had to be addressed as well.

Both active electronic- and optical feed-back loops had to be considered to reduce the noise levels of the millimeter wave mode-locked optical transmitter (MOT). We were to investigate theoretically the feasibility of further reduction of the noise levels of the mode-locked millimeter wave optical transmitter (M-MOT) by a long (~2-4 km) fiber-optic feedback delay line between the laser output and the millimeter wave oscillator.

ACHIEVEMENTS OF THE RESEARCH

I. NETWORK STUDIES

The theoretical investigations were mainly concerned with the most important performance parameters of the fiber optic/wireless systems: attenuation, noise figure, dispersion aspects.

Attenuation: The overall (measured at the electronic ends) attenuation of the system can be described according to the $L=b{\cdot}L^2_r$ expression, where L_r stands for the attenuation of the optical path, b factor depends on the applied modulation technique and the electronic matching circuits.

Noise figure: In our model we used five different noise current sources: generator noise, shot noise, RIN, photodiode noise and receiver amplifier noise sources. According to this model we found how the power of our optical signal influences the overall signal performance (by means of expressing the noise figure). Measurements were also done for verification purposes.

Dispersion: A special effect of the dispersion characteristics of the optical transmission media comes forward as we measure the modulated optical signal strength as a function of optical distance and the modulation frequency.

Beside these issues, drawbacks of the optical/wireless systems were also taken into investigation: modulation suppression because of the modulator characteristics, phase noise generation, modulator nonlinearities. Effects of these 3 drawbacks were tested for the case of different modulation techniques (QAM, OFDM, etc.)

In the followings, some of the most important results of our work will be represented by diagrams with reference to the previous description.

I.1. Loss in Radio over Fiber (RoF) systems

Loss of direct modulated optical-link

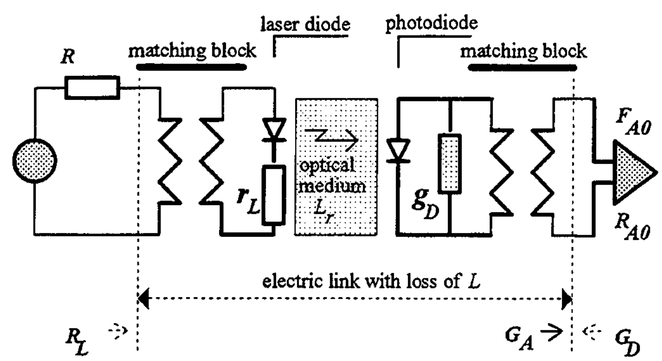


Fig. I. 1. Microwave model of a direct modulated fiber-optic link for loss and noise figure investigations

$$L = bL_r^2$$

$$b = \frac{RG_A}{4\left(M\eta_L\eta_Q\right)^2}\left(1+\frac{R_L}{R}\right)^2\left(1+\frac{G_D}{G_A}\right)^2\frac{r_L g_D}{R_L G_D}$$

Loss of externally modulated optical-link (using Mach-Zehnder as an external modulator)

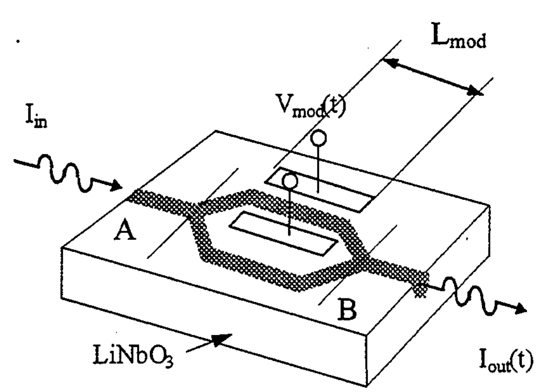


Fig. I. 2. $LiNbO_3$ Mach-Zehnder modulator

Loss characteristics of externally modulated optical link in case of a lumped parameter Mach-Zehnder modulator.

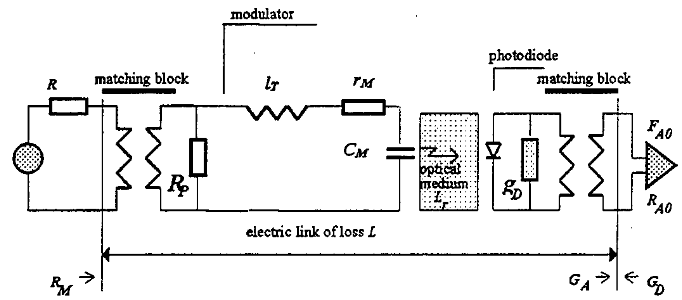


Fig. I. 3. Microwave model for an externally modulated fiber-optic link for loss investigations

$$b=\left(\frac{hf}{2\eta_Q Me}\frac{S}{P_{opt,in}}\right)^2\left(1+\frac{R_M}{R}\right)^2\left(1+\frac{G_D}{G_A}\right)^2\frac{RG_A g_D r_M}{R_M G_D}\omega_c^{\,2}$$

Loss characteristics of externally modulated optical link in case of a traveling wave Mach-Zehnder modulator.

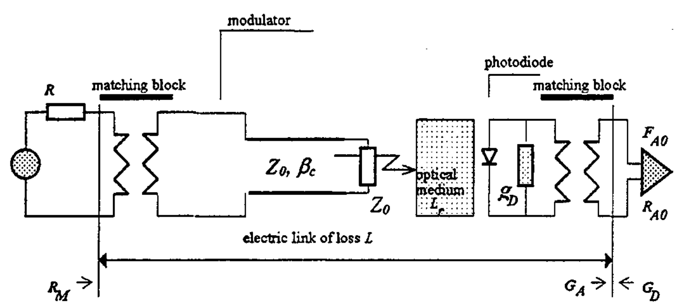


Fig. I. 4. Microwave model for an externally modulated fiber-optic link with travelling wave Mach-Zehnder modulator

$$b=\left(\frac{hf}{2\eta_Q Me}\frac{V_\pi}{P_{opt,in}}\frac{\psi}{\sin\psi}\right)^2\left(1+\frac{R_M}{R}\right)^2\left(1+\frac{G_D}{G_A}\right)^2\frac{RG_A g_D}{R_M Z_0 G_D}$$

In the present case b is also increasing with increasing frequency, like in the lumped capacitor design, however, this increase is much slower. Further note that in contrast to the previous cases, b is inversely proportional to Z_0; thus a high impedance transmission line is more advantageous than a low one. Of course, in the choice of the characteristic impedance the possibilities are not very wide. E.g. if an asymmetrical coplanar line is applied, taking reasonable dimensions characteristic impedances of 20...50 Ohm can be achieved.

I.2. Noise figure in fiber radio systems

Noise figure in direct modulated fiber radio links

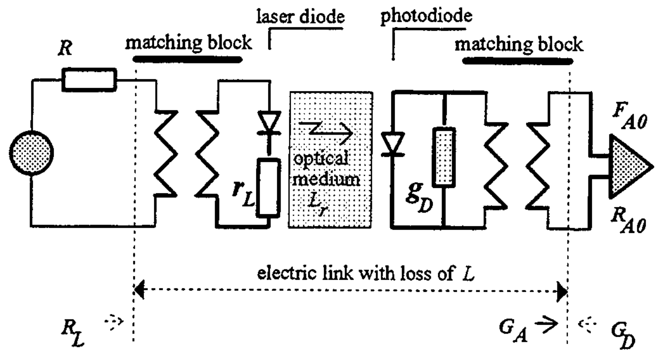


Fig. I. 5. Microwave model of a direct modulated fiber-optic link for noise investigations

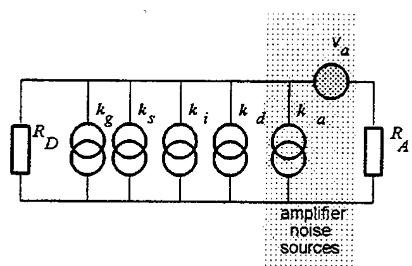


Fig. I. 6. Noise sources in the fiber-radio system

k_g: generator noise
k_s: shot noise
k_i: intensity noise (RIN)
k_d: photo diode noise
k_a, v_a: amplifier noise sources

Using such a noise model for the direct modulated fiber radio link the system noise figure is the following:

$$F = 1 + \frac{R_L}{R} + \frac{(R+R_L)^2 r_l}{RR_L}(a_0 + a_1 L_r + a_2 L_r^2)$$

where

$$a_0 = \frac{(I_0 - I_{th})^2}{4k_B T_0} RIN(\omega_c)$$

$$a_1 = \frac{e(I_0 - I_{th})}{k_B T_0} \frac{F_M}{\eta_L \eta_Q}$$

$$a_2 = \frac{1}{(\eta_L \eta_Q M)^2}\left[\frac{e}{k_B T_0} I_d + g_d + g_d \varphi(F_{A0} - 1)\right]$$

So the overall system noise figure is:

$$F = 1+\frac{R_L}{R}+\left(\frac{L_r}{\eta_L\eta_Q M}\right)^2\left(1+\frac{R_L}{R}\right)^2\left[\frac{G_D}{G_A}+(F_A-1)\right]RG_A+\frac{(I_0-I_{th})R}{2k_BT_0}(1+R_L/R)^2\left[e\frac{L_r}{\eta_L\eta_Q}F_M+\frac{I_0-I_{th}}{2}\mathrm{RIN}(\omega_c)\right]$$

To conclude this section it is mentioned that calculations similar to the calculations on dynamic range, on the effect of low noise amplifiers preceding the fiber-optic link etc. could be made in the case of an external modulator as well.

Effect of optical loss on system noise figure

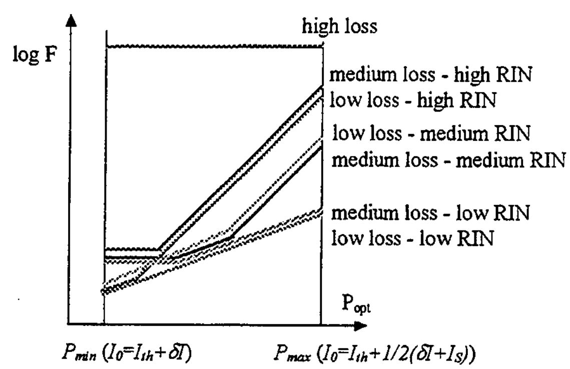


Fig. I. 7. Noise figure in special cases

Effect of dispersion on optical signal transmission as a function of distance and modulation frequency

In Fig.I.8. the attenuation of the modulating RF signal is shown vs. fiber length and modulating RF frequency.

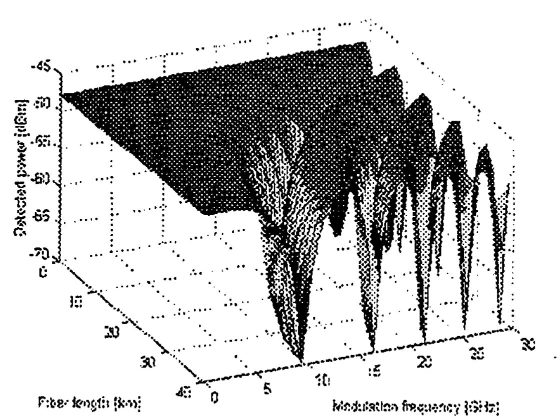


Fig. I. 8. Detected level of the optically transmitted fundamental MW signal vs. modulation frequency f_{RF} and fiber length L

II. NOISE REDUCTION IN MODE-LOCKED LASERS

Phase noise level of the system is determined mainly by the mode-locking RF source. We tried to suppress the phase noise of our RF source in two different ways:

1: we designed and fabricated a microwave oscillator operating with low noise pHEMT and utilizing a dielectric resonator as frequency determining element;

2: we developed and applied a new method for suppressing the phase noise of the microwave oscillator.

II. 1: The design procedure of the 20GHz microwave oscillator for mode-locking purposes

Here we will present the most important steps of the low noise 20GHz microwave oscillator design procedure, as well as the requirements that guided the design and the solutions for them we have found. In the next section (*2.*) we introduce a recently developed technique helping us to reduce the phase noise level of the signal coming out from our microwave oscillator.

We had some special requirements regarding to the oscillator to be built:

- that should be transistor based
- should operate with dielectric resonator
- should work exactly at 20GHz
- should fit in a housing not larger than 2.5x4 cm-s
- other technical requirements: good temperature stability, low phase noise, high frequency stability.

DR modeling

For being able to use a straightforward design procedure with DR, we could follow different methods:

- We could measure the DR coupled to a 50 Ohm transmission line at several positions (at a given distance from the input and at a given distance from the transmission line), and so, we could simulate the operation of it by inserting its S-parameters into the design. This choice has 3 main problems: measurement difficulties (inaccurate measurements), inflexible design (for not being able to optimize the location of the DR continuously), not taking into account the effects of the final housing.
- Having (or developing) a circuit model for the DR. The company (TransTech) from which we have purchased the DRs could provide parameter list for the modeling circuit of the DR (which gave the values of the parallel RLC as a function of frequency). After measurements, these data lists haven't been proven to be reliable.

Solution: We have to trust the reliability of the production method of TransTech, so we just use the fact that the DR should show resonance at 20GHz. Therefore, instead of a model, according to our measurement results, we have built S-parameter file which described the behaviour of a nearly ideal dielectric resonator. Obviously, after the production the circuit tuning procedure by experimental placing of the DR was needed to find the optimal coupling of the dielectric resonator to the circuit's transmission lines. (Too strong coupling would cause loaded Q degradation and so result in poor phase noise characteristics. In the case of too weak coupling the oscillator cannot "profit" from the utilization of the dielectric resonator.)

Substrate height

We have chosen Rogers 5880 Duroid because previously we had good experience with this material, it has low and almost constant permittivity through broad frequency range and that was a good RF substrate we could quite easily get at. Anyway, Rogers produces this substrate in several different heights. At our first trials we used 31mil Duroid. So we didn't have to take care of the effects of the small distance between the DR and the bottom side ground plane. The major drawback of this solution was that in that case we had to use many times wider transmission lines. According to our experience, using so wide transmission lines (eg. an 50Ohm Tline was like 2.55mm wide) we get side effects (radiations) that can mess up our whole design.

Solution: Finally we took the smaller height (10mil Duroid5880), though this way we have to employ a support ring for widening the distance between the DR and the bottom side ground plane.

Transistor

As active element we tried to use a FET of Alpha Ind. which had the type No.: AFM06P2-213. We got to this choice as we were looking for low noise RF transistor for which we could get the scattering parameters beyond the frequency of 20GHz. According to our measurements and simulation results we realized that Alpha Ind. couldn't measure and provide the S-parameters for their transistors accurately enough.

Solution: We had to step over to another transistor: to the ATF36077 low noise pHEMT of Agilent. We had good experience with the PHEMT ATF36163 so far, whose enhanced version is low noise ATF36077 pHEMT. (Although, we had to overcome the problem that Agilent could only provide the small signal S-parameters up to 18GHz. By extrapolation we could extend this data list up to 22GHz.)

The design process

Since we have to design a low noise, high power signal source we have got two conflicting tasks to solve at 20GHz:

- The transistor output and input matching networks are given that are close to the minimum noise adjustment of the transistor on the Smith-chart;
  - These matching networks should drive the transistor into maximal instability state. By optimization we can weight these two goals.

In Fig. II.1. a layout is shown for one of the functioning oscillators of us.

For reaching maximal instability we have to get into a situation where the load impedances (both at the output and the input sides) are in reciprocal relationship with the impedances of the transistor ports they are connected to. In ideal circumstances we could achieve infinite loop amplification inside of the oscillator. So, this part of the optimization is for reaching this situation at both ports of the transistor. The results of this can be checked by viewing the s11 parameters of the whole oscillator.

The other part of the optimization (for the low noise characteristics) can happen by simulating and constantly trying to reduce the noise by using the information of the optimum noise point of the Smith-chart (also provided with the S-parameter file).

After this optimization we are ready to build the matching circuits that show the appropriate impedance. For that we also needed to design biasing networks that don't have any effect at 20GHz, but can absorb the low frequency noises coming from the power supply. Except these low frequency parts of the oscillator we always tried to avoid the use of both discrete elements and vias that are not able to be described by S-parameter files well enough.

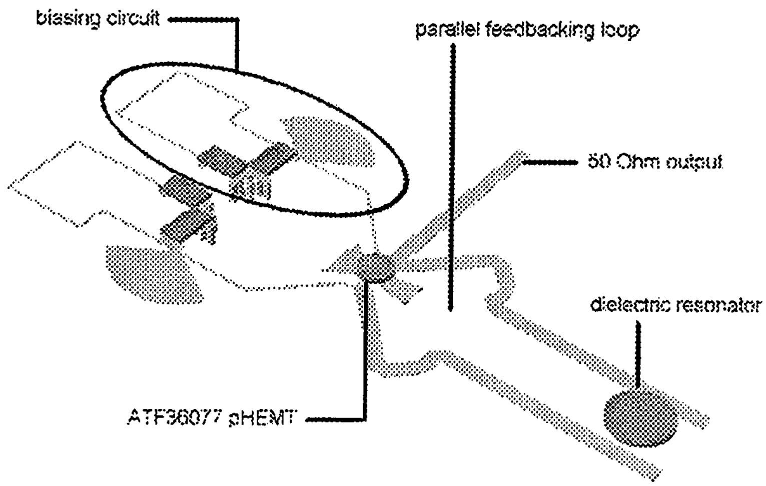


Fig. II. 1. Oscillator layout

Of course the whole matching circuit optimization can be done just after defining and optimizing the oscillator's basic structure: we have tried both series and parallel feedbacking schemes. We had isolating interdigital (or ATC) capacitor between the output matching circuit and the output.

The magnitude of reflection allows the circuit to oscillate exclusively around 20GHz, whereas the sharp slope of the phase characteristics defines the exact frequency of oscillation. Fig. II. 2. shows the simulation results after the optimization.

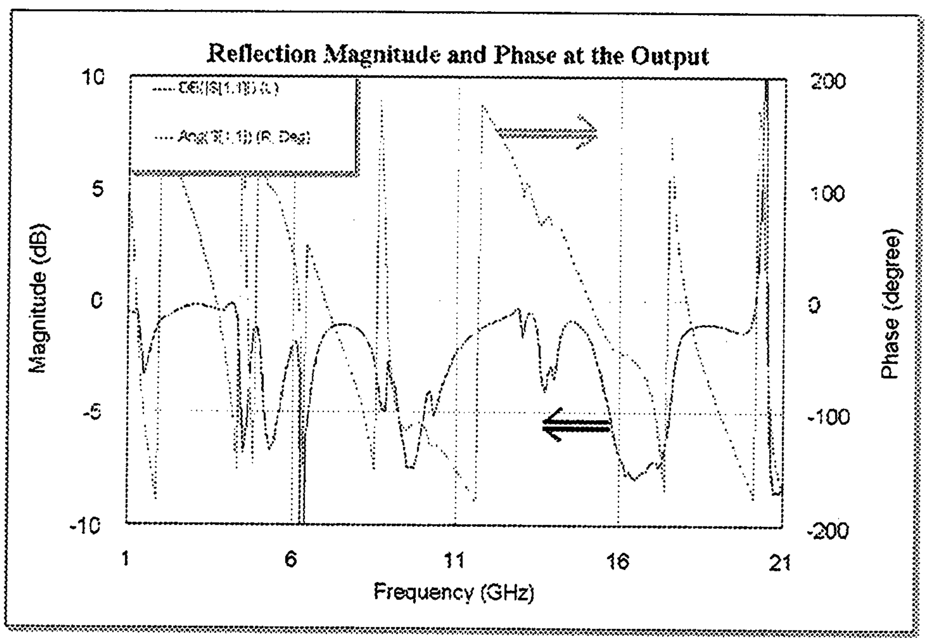


Fig. II. 2. Simulation results for magnitude and phase of the reflection

Measurement results:

The measured phase noise of our dielectric resonator oscillator was –44.68dBc/Hz @ 1kHz; -77.34dBc/Hz @ 10kHz; -98.89dBc/Hz @ 100kHz away from the carrier.

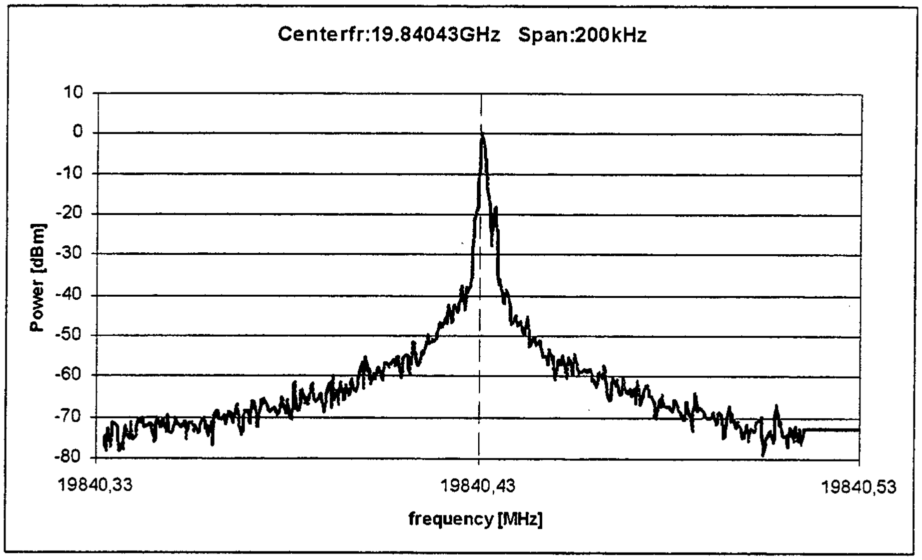


Fig. II. 3. The measured signal of the realized oscillator circuit

II. 2 Oscillator phase noise reduction by low frequency feedbacking

Theoretical Background

According to a well known phase noise generation concept the phase noise is originating from the active elements' flicker (1/f) noise. The signal of this noise source modulates the oscillator, so perturbating the frequency and amplitude of its output signal. That's why we can avoid (or at least reduce) this mixing process in two different ways: we may either linearize the amplifier (active element) to reduce the level of that mixing product; or we may reduce the level of the modulating noise signal. We took the second solution.

Since the signal of the noise source has a power spectral density function degrading by $1/f_\alpha$ ($\alpha \sim 1$), our problem of noise compensation should be low frequency (LF) problem. So, we can utilize LF signal controlling loop to reduce the instant level of the input noise. What we need is a good RF/LF isolation from the main oscillator circuit, and a signal conditioning LF feedback loop. If we "observe" the low frequency transmission characteristic function of the active element, and reverse its amplification by an attenuator, and add its output signal to our noise source with an overall –180° phase shift, we can compensate the signal of our noise source.

We have tested this concept in Agilent's ADS2001 RF simulation environment. The next subsection will introduce the buildup of the system and the simulation results we have achieved with it.

Simulation Results

The simulation system is shown in Fig. II. 4. As active element, we used Agilent's ATF-38143 low-noise pHEMT. We provided the simulator the noisy nonlinear Statz-model for that transistor. The upper loop is responsible for the normal RF oscillation and for the output power splitting. The dielectric resonator is modeled by a series attenuator – bandpass-filter pair. For the oscillation, the phase condition is set by the length of the two 50Ω transmission lines. The low frequency noise components were driven to the lower loop by a circulator – low-pass filter combination. This way the RF part (upper loop) was ideally isolated by the LF part (lower loop).

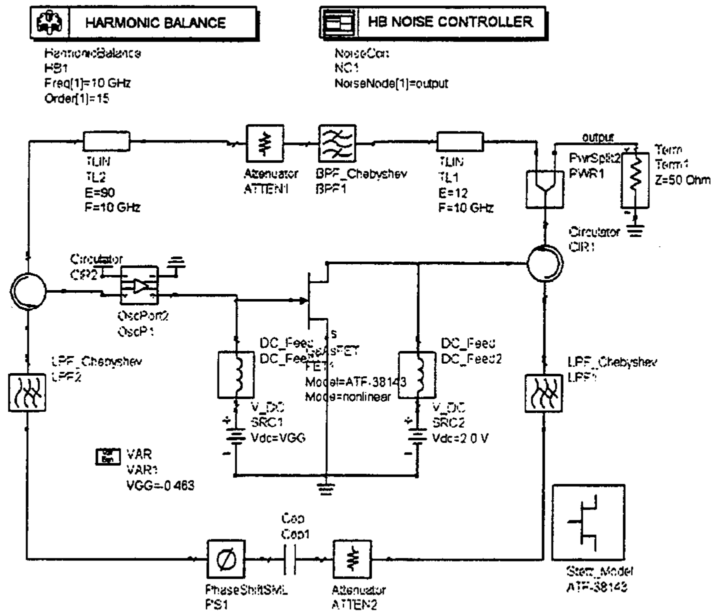


Fig. II. 4. Simulation setup for phase noise suppression

In the real experiments the circuit may be microstrip based: all the transmission lines, power splitter and bias circuits can be microstrip elements. Instead of the circulator – low-pass filter combination we designed a microstrip combining-filter which directs the low band signal to the lower loop and seems to be a short from the oscillator point of view. The LF compensation circuits is designed to contain LT1028 operational amplifier based variable phase shifter and variable attenuator circuits. The main building blocks of the above described experimental setup are already designed. Putting them together and validating the simulation results by real measurements is one of the next steps in of the near future.

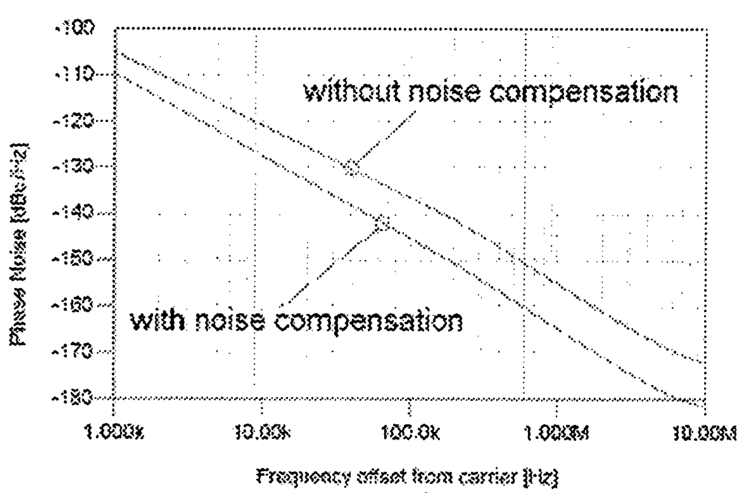


Fig. II. 5. Harmonic balance based noise simulation results with and without noise compensation

In Fig. II. 5. the harmonic balance based noise simulation results are shown. As it can be seen in the figure above, the LF compensation method gave significant phase noise reduction results (6-10dB reduction depending on the offset frequency from the carrier). We are further developing new techniques for reducing the phase noise level of the microwave oscillator.

III. INTENSITY NOISE SUPPRESSION IN MICRO-CHIP LASERS

Introduction

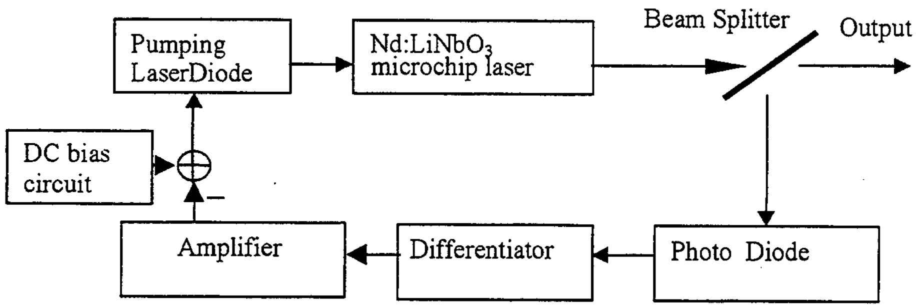
This part of the project is concerned with the suppression of the relative intensity noise (RIN) peak and phase noise of a diode pumped Neodymium-doped Lithium Niobate ($Nd:LiNbO_3$) microchip laser which is used in the MOT (Mode-locked Optical Transmitter) of the proposed network. Relaxation oscillations result in about 15-20 dB noise peak above the flat noise at 350 kHz offset frequency. In case of high quality requirements this noise peak is significantly disturbing. In this work a new approach is presented for the suppression of the RIN peak and phase noise in microchip lasers

Laser noise is a crucial parameter in many applications, like optically controlled phased array antennas, optically fed mobile radio base stations, high speed optical links, etc. Therefore significant effort is done to reduce the noise of lasers. The microchip laser exhibits a very low phase noise. However, it suffers from the relaxation resonance as every laser. At the relaxation resonance the noise has a high peak, 15-20 dB higher than that outside of the resonance region.

There have recently been a number of publications on the design and analysis of fiber radio systems using solid state microchip lasers. Herczfeld [3], Jemison et al. [4] have examined the applications of a $Nd:LiNbO_3$ mode locked laser in an LMDS system. Because of the good phase noise characteristics the optical generation of the local oscillator signal is feasible. However, the suppression of the close to carrier relaxation oscillations can improve the quality of the whole system. A number of feedback loops for different types of lasers have been evaluated and their corresponding advantages discussed. Kane [5] and Harb [6] have designed an electronic feedback for the reduction of intensity noise in a diode pumped Nd:YAG laser. Similarly, Geronimo [7] and Taccheo [8] have investigated the intensity noise reduction in an ytterbium-codoped erbium glass laser. In addition, the noise suppression with an external feedback was studied by Tsang-Der Ni [9]. Another possible way of RIN cancellation was presented by Madjar et al. [10] using balanced fiberoptic communication link.

III.1. Theory and Simulation

The block diagram of the feedback loop for noise suppression is depicted in Fig. II.b) 1. A fraction of the laser output signal is detected, differentiated, phase shifted, amplified and fed back to the pump laser DC supply.



Loop transfer function

The noise peak at 350kHz is reduced by using negative feedback. As the transfer function of the laser transmitter has a phase shift of almost -180° near the frequency where the gain of the open loop goes below unity, we have to realize positive phase shift in the amplifier following the low noise photodiode. To increase the phase noise sensitivity of the loop we use a differentiator circuit (phase shift +90°) with a zero near to the relaxation oscillation frequency and a pole at f=10MHz. The zero of the differentiator in the feedback circuit can compensate the effect of the complex conjugate poles of the microchip laser transfer function, which are responsible for the high noise peak. The additional pole at a higher frequency (10MHz) is only needed because of the stability of the differentiator circuit and does not have any effect in the frequency range of the peak. After the differentiation the phase shifted and amplified signal is added to the bias current of the pump diode.

Simulation

During the computer simulations the RIN peak of the solid state laser was modeled by the simple transfer function G(s);

$$G(s)=\frac{1}{1+2dTs+T^2s^2}=\frac{1}{1+2\cdot 10^{-8}s+2.06116\cdot 10^{-13}s^2} \quad (1)$$

where d is defined by Eq. (2) the value of the complex conjugate poles and so the height of the noise peak, and T gives the frequency of the resonance by Eq. (3).

$$d=\frac{R}{2}\sqrt{\frac{C}{L}} \quad (2) \qquad\qquad T=\sqrt{LC} \quad (3)$$

The RIN model has the transfer function G(s) therefore the transfer function of the closed loop is given by Eq. (4), where β(s) is the transfer function of the feedback system.

$$F(s)=\frac{G(s)}{1+G(s)\beta(s)} \quad (4) \qquad\qquad F(s)=\frac{G(s)}{1+G(s)\beta(s)e^{-s\tau}} \quad (5)$$

The Bode plot of the model is shown in Fig. III. 2. The results of the computer simulations are shown in Fig. III. 3. The real disturbing resonance term (open loop) stands out by 15-20 dB from the outside region [1].

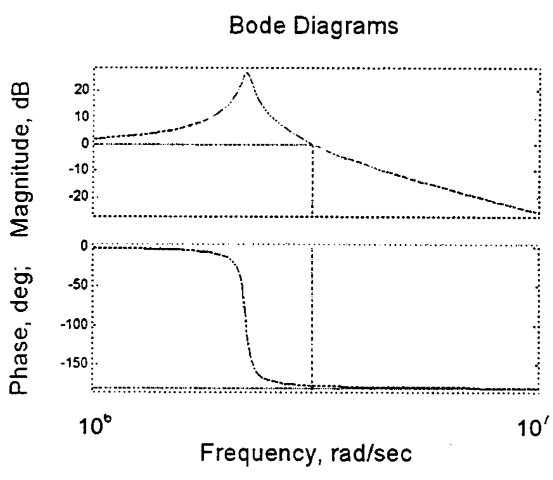


Fig. III. 2. Bode plot of the RIN model

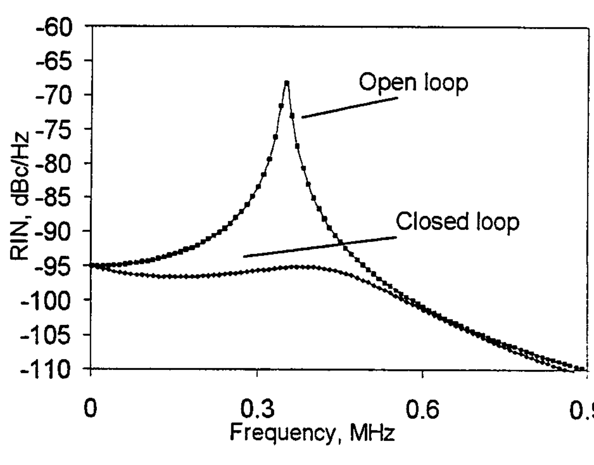


Fig. III. 3. Simulation results of RIN suppression

If the optical and electrical delay is taken into account the above expression should be changed to the form of Eq. (5). The time delay could cause instability in the system so it should be kept as law as possible.

The simulation results show an intensity noise suppression of ~20dB and a slight increase in noise at higher frequencies. Resetting the phase shift and the gain of the differentiator circuit in the feedback loop this small (~1dB) increase in noise can be shifted to lower or higher frequencies according to the application requirements, Fig. III. 4.

The Nyquist diagram of the simulated control loop is shown in Fig.III. 5. The instability point (-1,0) is not encompassed by the loop, so the loop is stable and has a maximum suppression at the relaxation oscillation frequency.

III. 2. Measurement results

Fig. III. 6. shows the measured relative intensity noise spectrum with and without the feedback loop. The laser signal was measured after the polarizing beam splitter by a photodiode, which was followed by a low noise transimpedance amplifier. The detected signal was differentiated and fed back to the biasing of the pump diode. Because of the negative phase shift of the differentiator, the control current could be added to the biasing current of the pump diode to realize the negative feedback. The results were recorded by a HP8593E Spectrum Analyzer.

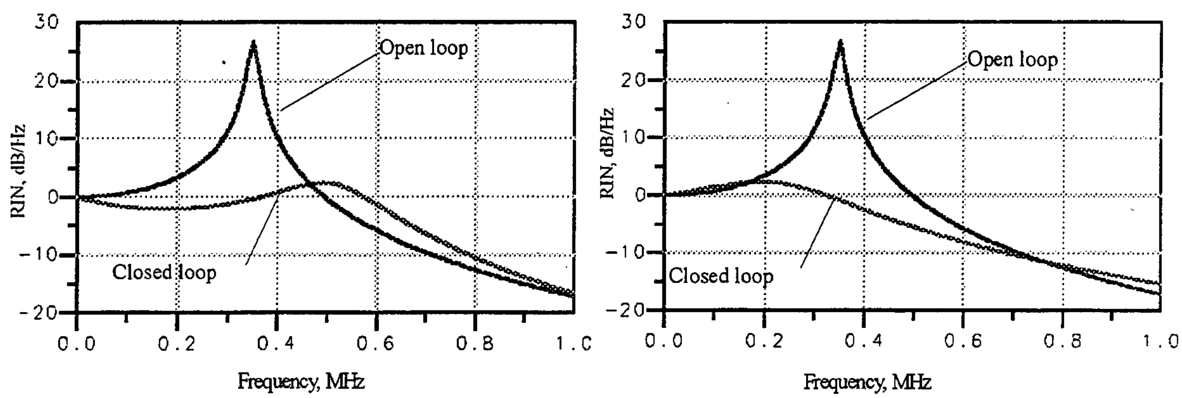


Fig. III. 4.The frequency of the suppression can be shifted setting the parameters of the feedback loop

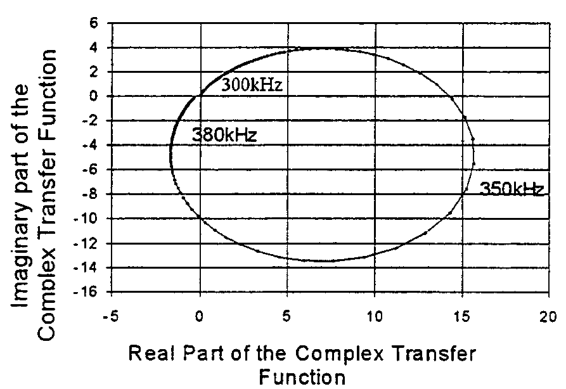


Fig. III. 5. The Nyquist diagram of the control loop. Maximum is at 350kHz in the pos.-neg. quadrant of the diagram. The instability point is not encompassed by the curve, hence the loop is stable.

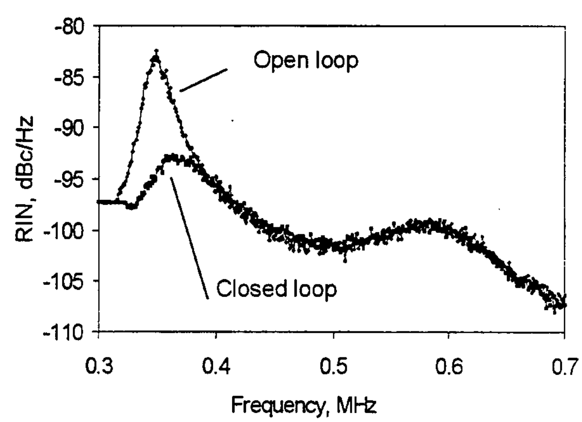


Fig. III. 6. The measured RIN suppression

Fig. III. 6. shows both the open and the closed loop relative intensity noise of the microchip laser. The noise peak is reduced by 13 dB due to the feedback loop. The noise level of the microchip laser can be further reduced, it is only limited by the noise of the measuring photoreceiver. When using low noise photodiodes the suppression at the relaxation oscillation can be increased.

The RIN suppression can be employed in case of other lasers too, such as pump laser diodes in Erbium-Doped Fiber Amplifiers (EDFA), in optical transmitters or in optical local oscillators.

III. 3. Conclusions

A system with capabilities both suppressing the RIN peak and reducing the phase noise of a Nd:LiNbO$_3$ microchip laser was demonstrated in this paper.

This approach applied a special feedback loop sensitive to the phase noise. First computer simulations were carried out. They provided very good results. According to them 15-20dB suppression was expected. Then experiments were performed. Their results proved the theoretical expectations. The RIN peak was suppressed by ~15dB.

SUMMARY

We have examined theoretically (mathematically) the optical/wireless systems, focused on their overall performance characteristics, which are needed as root data for system design. The limitations of such systems were determined by the derived mathematical expressions.

We developed a microwave signal source for mode-locking purposes, being intent on suppressing its noise power. We designed a new structure which can reduce the microwave oscillators' phase noise with the help of a low frequency feedback loop.

We designed an electrical feedback loop for overcoming a serious problem of the solid state laser mode-locking: the high level RIN at the relaxation oscillation frequency of solid state laser. Applying the feedback loop at least 13dB RIN peak suppression was attained at the relaxation oscillation frequency.

FUTURE PLANS

In spite of the already achieved good results previously presented, we are planning to further develop these results.

A more detailed computer simulation test is planned which aims the examination of optical/wireless systems according to the following aspects: modulation types which use the above described characteristics of optical signal dispersion; more detailed characterization of the effects of the nonlinearities and noise on the system bit error rate for the case of several modulation methods; remote heterodyning; practical requirements and limitations.

It is also planned to further improve the oscillator design, to develop microwave sources with reduced phase noise characteristics, e.g. new external noise suppression methods are under study as well.

Relative intensity noise (RIN) reduction is also essential for several other applications utilizing microchip lasers. Investigations on the opportunities regarding to these applications is of great interest. Noise reduction can be achieved by enhancing the loaded Q factor of either the mode-locking microwave source or the optical part of the system (with optical delay segment in an electro optical feedback loop; with electrical delay segment in the feedback loop; etc.).

References

[1] Márk Csörnyei, Tibor Berceli, Peter R. Herczfeld, Tamás Bánky, Tamás Marozsák, "A New Approach for RIN Peak and Phase Noise Suppression in Microchip Lasers", *International Microwave Symposium Digest*, pp. 1377-1380, Seattle, WA, June 2002.

[2] Tamás Bánky, Tibor Berceli "Two New Approaches for Phase Noise Improvements in Millimeterwave Dielectric Resonator Oscillators", *Proc. of the 32th European Microwave Conference* 2002, pp. 449-452, Milan, Italy, September 2002.

[3] Márk Csörnyei, Tibor Berceli, Tamás Bánky, "Microchip Laser RIN-Suppression for Fiber Radio Applications"URSI 2002, XXVIIth General Assembly of the International Union of Radio Science, Maastricht, Netherlands, August 2002.

[4] Tamás Bánky, Tibor Berceli "Phase Noise Characteristics Improvement of Hybrid Integrated Microwave Oscillators", 14th International Conference on Microwaves, Radar and Wireless Communications , Gdansk, Poland, May 2002.

[5] P. R. Herczfeld: "Overview of Microwave Photonics Activity under MARC", *Optical/WirelessWorkshop* Budapest, Hungary, 12 March 2001

[6] W. D. Jemison, P. R. Herczfeld, W. Rosen, A.Vieira, A. Rosen, A. Paolella, A.Joshi: "Hybrid Fiberoptic-Millimeter Wave Links", *IEEE Microwave Magazine* Vol.1, Number 2, June 2000

[7] T. J. Kane. "Intensity Noise in Diode-Pumped Single-Frequency Nd:YAG Lasers and its Control by Electronic Feedback", *IEEE Photonics Technology Letters*, Vol.2. No.4. April 1990

[8] C.C. Harb, M.B. Gray, H.-A. Bachor, R. Shilling, P. Rottengatter, I. Freitag, H. Welling: "Suppression of the intensity noise in a diode-pumped Neodymium:YAG nonlinear ring laser", *J.of Quantum Electronics*, vol.30, No.12, pp. 2907-2913, December 1994

[9] G. De Geronimo, S. Taccheo, P.Laporta: "Optoelectronic feedback control for intensity noise suppression in a codoped erbium-ytterbium glass laser", *Electron. Lett.*, vol. 33, pp.1336-1337, 1997

[10] S. Taccheo, P. Laporta, O.Svelto, G. De Geronimo:" Intensity noise reduction in a single-frequency ytterbium codoped erbium laser", *Optics Lett.*, vol. 21, No. 21, pp. 1747-1749, Nov 1, 1996

[11] Tsang-Der Ni, Xiangdong Zhang, Afshin S. Daryoush: "Experimental Study on Close-In to Microwave Carrier Phase Noise of Laser Diode with External Feedback", *IEEE Transactions on Microwave Theory and Techniques*, vol.43, No.9, September 1995.

[12] A. Madjar, O. Malz: "A balanced fiberoptic communication link featuring laser RIN cancellation", *IEEE MTT-S Digest*, 1992

[13] T. Marozsák, E. Udvary, T. Berceli: "A combined optical-wireless broadband Internet access: transmission challenges", *IEEE MTT International Microwave Symposium Digest*, pp. 997-1000, Phoenix, USA, May 2001

[14] T. Berceli, G. Járó, T. Marozsák, S. Mihály, E. Udvary, Z. Varga, A. Zólomy: "A New Optical Signal Distribution Method for Phased Array Antennas at Millimetre Waves", *Proceedings of the 5th International Conference on Radar System*, Session 2.2, Brest, France, May 1999

[15] Frigyes: „Loss and noise ..." ,Chapter 1 in Al-Raweshidi, Komaki ed.: Radio over Fiber, *Artech House*, 2001 (in press)

[16] COST 235, Radiowave propagation effects on next generation..., *final report, Luxemburg*, 1966

[17] Frigyes, Szabó, Ványai: „Digital microwave communications", Amsterdam, Budapest, *Elsevier-Akadémiai Kiadó*, 1989

[18] Hanzó: „Bandwidth-efficient wireless multimedia communications", *Proc IEEE*, Vol. 86, No 7, pp. 1342-1382, July, 1998

[19] Proakis: „Digital communications", New York etc., *McGraw Hill*, 1998
[20] Foschini, G.J., M.J. Gans: „On limits of wireless communications…" *Wireless Personal Comm.*, Vol. 6, No. 3, pp. 311-335, Mar. 1998
[21] Agraval, D & al: „Space-time codes…" *IEEE Trans IT*, Vol. 44, pp. 744-765, Mar. 1998
[22] Naguib, A.F & al., „A space-time coding modem…" *IEEE J.-SAC*, Vol. 16, pp. 1459-1477, Oct. 1998
[23] Webb, Hanzó: „Modern Quadrature Amplitude Modulation", London, *Pentech Press*, 1994
[24] Braithwaite: „Using Walsh-code selection to reduce the power variance of band limited forwardlink CDMA waveforms", *IEEE SAC* Vol.18 No 11, pp. 2260-2269, Nov. 2000
[25] Gliese, U., S. Nørskov, T.N. Nielsen: "Chromatic dispersion in fiber-optic microwave and millimeter-wave links", *IEEE Trans. MTT*, Vol. 44, No. 10, pp. 1716-1724, Oct. 1996
[26] Frigyes, I., A. Hilt, S. Csernyin: „Investigations in microwave optical links…" *MWP 2000* paper No. WE2.2, 11-13 Sept, 2000, Oxford UK
[27] Izutsu, M., S. Shikama, T. Sueta: „Integrated optical SSB modulator/frequency shifter", *IEEE J. Quant. Electr.*, Vol. QE-17, No. 11, pp. 2225-2227, Nov. 1981
[28] Berceli, T. & al.: „Millimeter-wave generation by optical means", *MIKON 2000*, Wroclaw, Poland, May 2000
[29] Wake, D., C. R., Lima, P. A. Davies: „Optical generation of millimeter-wave signals for fiber-radio systems using a dual-mode DFB semiconductor laser", *IEEE Trans. on MTT*, Vol. 43, No. 9, pp.2270-2276, Sep. 1995
[30] Jemison & al.: „Fiber radio using mode-locked microchip…"
[31] Betti, de Marchis, Iannone: „Coherent optical communication systems," New York, etc., *Wiley*, 1995
[32] Braun & al.: „Transmission experiments with optically generated carriers in the 60 GHz region", *Wireless Pers. Comm.*, Vol. 14, No. 2, Aug. 2000, pp. 85-101
[33] Agrawal, G. P.: „Nonlinear fiber optics", San Diego etc., *Academic*, 1995
[34] Ochiaci, H., H. Imai: „On the distribution of the peak-to-average ratio in OFDM signals", *IEEE Trans on Com*, Vol 49, pp. 282-289, Feb. 2001
[35] Agrawal, G. P.: „Fiber-optic communication systems", New York etc., *Wiley*, 1992
[36] Rappaport: „Wireless communication", New York, *IEEE Press*, 1996
[37] Walke: „Mobile radio networks", Chichester etc. *Wiley*, 1999