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# Optical Switching Applications of Delayed Feedback Nonlinear Systems

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Contents:

# I. Planning and System Design

The goal of this project was to develop an optical switching system based on an optical nonlinear delayed-feedback system previously developed at ATR by T. Aida and P. Davis. A secondary task was optimizing the feedback system for the switching application. Nonlinear delayed-feedback systems are useful because for a relatively simple implementation they exhibit a wide range of complex functions, such as data storage, random data generation, and adaptive data generation.

The primary project was to set up an optical switching system using the output of the nonlinear fiber-delayed-feedback system. The switching technique that was chosen is direct injection of an optical pump signal into a lasing device. Optical switching has previously been demonstrated in traveling-wave or Fabry-Perot optical amplifiers using a separate CW laser as the probe source. However, direct injection is a simpler technique combining the optical source and wavelength conversion mechanism into a single device.

The lasers used in this experiment are conventional single-stripe long-wavelength lasers which are available commercially. Lower switching thresholds have been demonstrated using a multisegment laser with a saturable absorber to quench lasing in the absence of a pump signal. The saturable absorber also induced bistability, which is an interesting subject for further investigation. Bistable devices were not readily available for use here. Distributed feedback (DFB) lasers were used to provide single-frequency output.

The price of pigtailed lasers is about an order of magnitude higher than for chip-mounted or can-mounted devices. The cost of building a general-purpose fiber pigtailing setup is comparable to buying a pigtailed laser. However, a general-purpose setup can be used to compare switching in many different kinds of lasers at relatively low cost. For example, Fabry-Perot lasers vs DFB lasers, and gain-depletion pumping vs gain-enhancement pumping.

A major component of the project was construction of a 1.3μm semiconductor optical amplifier. A commercially available Erbium-doped fiber amplifier was used to get high-power signals for switching at 1.55um. A semiconductor amplifier can be used to directly do optical switching in the amplifier itself due to gain saturation or four-wave mixing. A semiconductor amplifier was constructed for backup as a 1.3um amplication source as well as a frequency-conversion component.

# II. Nonlinear System Optimization

This section discusses optimization of the nonlinear feedback system for repetition rate and output power. A high pulse repetition rate (greater than 100MB/s) is important in order to demonstrate the relevance of this work to current optical switching problems. Repetition rate problems that were addressed are loop delay and frequency response flatness.

High output power is desirable to minimize the amount of amplification needed for optical switching. High power is particularly important because this type of system has a fairly small contrast in power between the '1' (high power) state and '0' (low power) state.

Two nonlinear feedback systems had been built at ATR prior to the start of this research project. The first is a low frequency demonstration version which has a maximum clock frequency of 25.5 MHz and uses a 1.3μm laser. The second is a high performance system with a theoretical maximum clock frequency around 1 GHz that uses a 1.55μm laser. This switching work focused on the second system in order to achieve high switching rates.

Nonlinear feedback systems require flat frequency response from the fundamental oscillation frequency (1/4 times the loop delay) to about 3-5 times the highest desired oscillation frequency in order to allow the harmonics associated with fast transitions. A very small amplitude imbalance <0.5dB has been shown by Aida and Davis (JQE 1992) to cause preferential selection of particular bit patterns.

The frequency response of the optical modulator/detector response is shown in figure 2. The resonance around 20 MHz is associated with the acoustic resonant of the modulator, which is coupled into the optical performance by the piezoelectric effect. The nonlinear system had a strong tendency to lock into this resonance.

The first problem to be solved is the effect of this resonance. The resonance itself is not easily eliminated. It is important to push the total nonlinear loop delay time above this 20 MHz resonance by minimizing the amplifier delay and electrical and optical path delays. Minimizing the loop delay also has the important benefit of increasing the repetition rate for a given bit length pattern, allowing for faster switching demonstrations. This delay was minimized in collaboration with P. Davis and T. Aida by shortening the electrical and optical path lengths.

When building very broadband microwave amplifiers, small resonances unavoidable occur the frequency response. Cascading amplifiers for higher gain also increases the amplitude of gain ripple, frequently to unacceptable levels. The amplifier chain should be composed of amplifiers each with a different design to avoid cascading resonances. Ideally the amplifiers would even be from different manufacturers. However, one of the goals is to include DC response, and there are few sources of high-frequency DC-coupled sources.

The bandwidth of the components is sufficient to allow GHz oscillation. However, due to the frequency ripple, equalization of the frequency response is essential in order to realize this GHz potential. Figure 3 shows the initial design of an equalizer, and a general equalizer design which can be built and then customized for various ripple functions. A design was optimized and constructed by Nogawa. Using this equalizer, GHz oscillation was achieved. In order to limit the number of data bits in the system, coaxial low-pass filters were purchased from Mini-Circuits. By using different bandwidths, the number of bits in the system was varied from 3 to 21.

The optical modulator had about 3dB higher loss than originally measured at the factory. With more optical power and reduced loss in the optical modulator, it should be possible to get oscillation with only two amplifiers, reducing the delay and ripple of the system.

Further work to be done on optimizing the system are:
(a) Reduce insertion loss of the modulator
(b) Shorter fiber leads on the modulator
(c) Further equalizer optimization
(d) Use a higher-power laser

# III. Experimental Results

A key task in this switching project was getting good coupling from the laser into the fiber. Both a Hoya A85 aspheric lens and an NSG gradient-index lens were used with good results. It was not possible to measure the absolute coupling efficiency, as a broad area photodetector would be needed to capture all of the light. The NSG lens has a very high numerical aperture, and should capture most of the light emitted from the laser. Both lenses were able to get a coupling efficiency of 3dB compared to the light collimated by the NSG lens.

A 1.3 semiconductor optical amplifier was designed and assembled using an NTT Electronis amplifier chip. The switching demonstration ended up being done at 1.55um, and the amplifier was not used in the experiment.

Several switching options were investigated. The first was optical pumping. In this approach the output of the nonlinear system would be in the absorption band of another laser. When the nonlinear system signal pump was on, it would generate carrier in the probed laser which would decrease the threshold and increase the output power. This is a noninverting switching operation. This was attempted with the pump laser at 1.3um and the probe laser at 1.55um. However, very little modulation of the probe laser, with 1mW of pump power producing a few tens of uW in the probe laser. Apparently the absorption of the 1.55um probe lasers is not sufficiently high at 1.3um.

The second approach was polarization switching. In this approach, the laser has a desired polarization (usually TE). The opposite polarization (usually TM) is injected, causing the laser to switch polarization. A polarizer following the laser converts the polarization switching to amplitude modulation. This was also attempted, but although a variety of lasers were tested, all of them exhibited a strong preference for TE polarization, and would not switch.

The final switching method that was tested was injection locking. In this method a signal is injected which is at a different wavelength from the lasers natural frequency, causing the lasers wavelength to change. An optical filter can be used to convert the wavelength change to amplitude modulation. This switching technique was tested with a number of lasers at both 1.3um and 1.55um, and was universally successful.

Finally, the optical system was used as a source of control signals for driving a WDM signal switching system. A novel implementation shown in Figure 4 was developed which exploits the repetitive nature of the optical system output in order to obtain complementary switched signals from identical switching systems. A technique for implementing this approach was developed by splitting the pump pulse and combining the two output pulses using a polarization coupler. This configuration is optimum for polarization switching. It can also be used for injection locking, and has the useful property that the two lasers are combined with orthoganol polarizations, which is helpful for separating them without an optical filter.

DFB lasers were used as the probe devices, since WDM (wavelength division multiplexing) implies that the output is at a particular wavelength, while Fabry-Perot lasers have an output at many wavelengths. The final configuration used an NEC laser at 1545.*nm and a Mitsubishi laser at 1549.*nm. The pump laser was a Fujitsu laser at 1552.*nm. Using different manufacturers was very helpful in getting different wavelengths, as lasers ordered from one source tended to be at the same wavelength, particularly if ordered at the same time.

An optical filter was implemented by collimating the light from the fiber, reflecting it off of a grating, and coupling the light back into another fiber. This filter was used to separate the pump and probe signals for time-domain analysis. This filter had a bandwidth of a few nm, and a loss of more than 6dB. The reflectivity of the grating was 60%. The origin of this high loss needs further investigation, but it could be due to either the long path length or imperfections in the grating. The fiber to fiber spacing was about 4cm. Long distance between the gradient index fiber couplers leads to increased loss as the beam front quality tends to degrade with distance. The grating surface quality appeared to be poor, which can also lead to increased coupling loss due to beam front degradation.

The switching characteristics were examined using an HP8112A pulse generator into the optical modulator. The rise and fall time of the outputs was approximately equal to the rise and fall time from the modulator, which was on the order of 2ns. This indicates that the switching time is <2ns.

Switching was done using several different bit patterns which were selected from the nonlinear system by varying the microwave low-pass filter which limits the number of bits in the system. Figure 5a shows the output from the NEC and Mitsubishi lasers using the 933MHz filter. Complementary output patterns occur due to the 3m fiber delay from the coupler to the NEC laser. The intensity modulated pattern directly from the nonlinear system is transformed to on/off pulse information by the thresholding effect of the switching. Figure 5b shows the output of the Mitsubishi laser using the 1830MHz filter. From this data, optical switching time of the lasers is <1ns.

# IV. Conclusion

The goal of this project was to use the nonlinear feedback system for WDM/routing optical switching. The nonlinear system was optimized for this purpose, and the output was used to switch two lasers at different wavelengths with a complementary bit pattern.

# V. Acknowledgments

We would like to thank T. Watanabe for his support and encouragement. We would like to thank T. Aida (NHK) for his assistance in optimizing the nonlinear system hardware for optical switching. We would like to thank T. Miyazaki, K. Inagaki, H. Kawamura, and H. Shimotaira for lending advice and equipment, and M. Hosoda for his expertise with oscilloscopes and endless supply of miscellaneous parts.

# Appendix 1: Mechanical design

Mechanical parts were designed for a number of purposes related to optical switching and for a semiconductor optical amplifier. This is a description of general mechanical parts that were designed, and their purpose.

| *Part* | *Purpose* |
|---|---|
| Aspheric Lens Holder | permanently mount laser-fiber focusing lenses |
| Aspheric Lens Tube | mount collimating or focusing lenses |
| Base Modification | make Fiber Base and Mounting Base from commercial part |
| Beam Collimator Holder | hold fiber collimators on stand or in mirror mount |
| Chip Carrier Mount | attach chip-mounted lasers to TE cooler |
| DIN Connector Bracket | attack DIN connector to Mounting Plate |
| Dual Aspheric Lens Holder | mount collimating lens and hold lens tube |
| FC Holder Stand Mount | hold FC fiber optic connector for coupling |
| FC Rotation Base | hold FC Rotation Plate |
| FC Rotation Plate | hold and rotate polarization preserving fiber |
| Fiber Base | hold Fiber Rotation Plate on 5-axis positioner |
| Fiber Strain Relief | prevent fiber movement from degrading coupling |
| Grating Mount | mount and protect grating |
| GRIN Lens Holder | mount GRIN SELFOC lenses |
| Lens Arm | attach various lens holders to XYZ positioner |
| Lens Arm Rest | protect lenses in box |
| Mounting Base | attach Mounting Plate to XYZ positioner fixed plate |
| Mounting Plate | hold laser/TE cooler and DIN Connector Bracket |
| Pigtailed Laser Plate | hold butterfly laser packages, fits standard cover |
| Submarine Can Mount | hold submarine laser can packages |
| Thor 6mm Lens Mount | hold Thor Labs aspheric lens mount |

This is a description of semiconductor amplifier parts. The semiconductor amplifier also uses some of the general parts listed above.

| *Part* | *Purpose* |
|---|---|
| Amplifier Lens Arm | attach Dual Aspheric Lens Mount to XYZ positioner |
| Aspheric Tube Clamp | clamp Isolator Assembly to Semiconductor Amp Stand |
| Cable Clamp | hold wires on amplifier assembly |
| DIN Angle Bracket | attach DIN connector to amplifier assembly |
| Dual Aspheric Lens Mount | hold Isolator Assembly near amplifier |
| Isolator Assembly | hold isolator and lens tubes |
| Semiconductor Amp Base | hold Semiconductor Amp Stand |
| Semiconductor Amp Stand | hold semiconductor amplifier |
| TE spacer | use in place of thermoelectric cooler |

# Appendix 2: Related Literature

The following is a reference list of papers related to this work. Many of these papers have optical bistability as the main topic, but also discuss optical switching.


1. M. J. Adams, H. J. Westlake, M. J. O'Mahony, I. D. Henning, "A comparison of active and passive optical bistability in semiconductors", IEEE J. Quantum Electron., QE-21, 1498-1504 (1985).

2. T. Aida, P. Davis, "Oscillation modes of laser diode pumped hybrid bistable system with large delay and application to dynamical memory", IEEE J. Quantum Electron., 28, 686-699 (1992).

3. T. Aida, P. Davis, "Oscillation mode selection using bifurcation of chaotic mode transitions in a nonlinear ring resonator", to be published in IEEE J. Quantum Electron.

4. S. B. Alexander, et al., "A precompetitive consortium on wide-band all-optical networks", J. Lightwave Technol., 11, 714-735 (1993).

5. P. E. Barnsley, P. J. Fiddyment, "Wavelength conversion from 1.3 to 1.55μm using split contact optical amplifiers", IEEE Photon. Tech. Lett., 3, 256-258 (1991).

6. C. A. Brackett, "Dense wavelength division multiplexing networks: principles and applications", IEEE J. Select .Areas Commun., 8, 948-964 (1990).

7. Y. C. Chen, J. M. Liu, "Polarization bistability in semiconductor lasers", Appl. Phys. Lett., 46, 16-18 (1985).

8. M. W. Derstine, et al., "Alternative paths to chaos in optical bistability", Phys. Rev., 27, 3200-3208 (1982).

9. S. Dubovitsky, P. D. Dapkus, A. Mathur, W. H. Steier, "Wavelength conversion in a quantum well polarization insensitive amplifier", IEEE Photon. Tech. Lett., 6, 804-807 (1994).

10. T. Durhuus, C. Joergensen, B. Mikkelsen, R. J. S. Pedersen, K. E. Stubkjaer, "All optical wavelength conversion by SOA's in a Mach-Zehnder configuration", IEEE Photon. Tech. Lett., 6, 53-55 (1994).

11. T. Fujita, A. Schremer, C. L. Tang, "Polarization bistability in external cavity semiconductor lasers", Appl. Phys. Lett., 51, 392-39 (1987).

12. M. Fujiwara, et al., "A coherent photonic wavelength-division switching system for broad-band networks", J. Lightwave Technol., 8, 416-422 (1990).

13. R. J. Gibbens, F. P. Kelley, P. B. Key, "Dynamic Alternative Routing-Modelling and Behaviour", ITC, pp. 3.4A.3.1 (1988).

14. B. Glance, et al., "High performance optical wavelength shifter", Electron. Lett., 28, 1714-1715 (1992).

15. B. S. Glance, J. M. Wiesenfeld, U. Koren, R. W. Wilson, "New advances on optical components needed for FDM optical networks", J. Lightwave Technol., 11, 882-889 (1993).

16. G. Grosskopf, R. Ludwig, H. G. Weber, "140 Mbit/s DPSK transmission using an all-optical frequency convertor with a 4000 GHz conversion range", Electron. Lett., 24, 1106-1107 (1988).

17. R. Hui, Q. Jiang, M. Kavehrad, T. Makino, "All-optical phase modulation in a traveling wave semiconductor laser amplifier", IEEE Photon. Tech. Lett., 6, 808-810 (1994).

18. R. Hui, A. Paradisi, S. Benedetto, I. Montrosset, "Dynamics of optically switched bistable laser diodes in the injection-locked state", Optics Lett., 18, 1733-1735 (1994).

19. P. P. Iannone, P. R. Prucnal, "Multinanometer wavelength conversion of 2.5 and 10 Gb/s optical channels in an injection-locked semiconductor laser", IEEE Photon. Tech. Lett., 6, 988-991 (1994).

20. K. Ikeda, "Multiple-valued stationary state and its instability of the transmitted light by a ring cavity system"", Opt. Commun., 30, 257-261 (1979).

21. K. Ikeda, H. Daido, "Optical turbulence: Chaotic behavior of light from a ring cavity", Phys. Rev. Lett., 45, 709-712 (1980).

22. K. Ikeda, K. Kondo, "Successive higher-harmonic bifurcations in systems with delayed feedback", Phys. Rev. Lett., 49, 1467-1470 (1982).

23. K. Ikeda, K. Matsumoto, "High-dimensional chaotic behavior in systems with time-delayed feedback", Physica, 29D, 223-235 (1987).

24. T. Ikegami, "Reflectivity of mode at facet and oscillation mode in double-heterostructure injection lasers", IEEE J. Quantum Electron., QE-8, 470-476 (1972).

25. K. Inoue, "High-speed all-optical gate switching experiment in a Fabry-Perot semiconductor laser amplifier", Electron. Lett., 23, 921-922 (1987).

26. K. Inoue, "Arrangement of fiber pieces for a wide wavelength conversion range by fiber four-wave mixing", Optics Lett., 19, 1189-1191 (1994).

27. K. Inoue, K. Oe, "Optically triggered off-switching in a bistable laser diode using a two-electrode DFB-LD", Electron. Lett., 24, 512-513 (1988).

28. C. Joergensen, T. Durhuus, C. Braagaard, B. Mikkelsen, K. E. Stubkjaer, "4 Gb/s optical wavelength conversion using semiconductor optical amplifiers", IEEE Photon. Tech. Lett., (1993).

29. H. Kawaguchi, "Bistable operation of semiconductor lasers by optical injection", Electron. Lett., 17, 741-742 (1981).

30. H. Kawaguchi, "Optical bistable-switching operation in semiconductor lasers with inhomogeneous excitation", Proc. IEE, 129, 141-148 (1982).

31. H. Kawaguchi, "Optical input and output characteristics for bistable semiconductor lasers", Appl. Phys. Lett., 41, 702-704 (1982).

32. S. Kawanishi, H. Takara, M. Saruwatari, T. Kitoh, "Ultrahigh-speed phaselocked-loop-type clock recovery circuit using a travelling-wave laser diode amplifier as a 50 GHz phase detector", Electron. Lett., 29, 1714-1716 (1993).

33. M. Koga, N. Tokura, K. Nawata, "Gain-controlled all-optical inverter switch in a semiconductor laser amplifier", Appl. Opt., 27, 3964-3965 (1988).

34. J. P. R. Lacey, M. V. Chan, R. S. Tucker, A. J. Lowery, M. A. Summerfield, "All-optical WDM to TDM transmultiplexer", Electron. Lett., 30, 1612-1613 (1994).

35. P. J. Legg, D. K. Hunter, I. Andonovic, P. E. Barnsley, "Inter-channel crosstalk phenomena in optical time division multiplexed switching networks", IEEE Photon. Tech. Lett., 6, 661-663 (1994).

36. L. Li, "A unified description of semiconductor lasers with external light injection and its application to optical bistability", IEEE J. Quantum Electron., 30, 1723-1731 (1994).

37. H.-F. Liu, T. Kamiya, "Temperature dependence of bistable InGaAsP/InP lasers", IEEE J. Quantum Electron., QE-22, 1579-1586 (1986).

38. J. M. Liu, Y. C. Chen, "Digital optical signal processing with polarization-bistable semiconductor lasers", IEEE J. Quantum Electron., QE-21, 298-306 (1985).

39. A. Marrakchi, Eds., Photonic Switching and Interconnects (Marcel Dekker, New York, 1994).

40. A. Mecozzi, "Analytical theory of four-wave mixing in semiconductor amplifiers", Optics Lett., 19, 892-894 (1994).

41. B. Mikkelsen, et al., "Wavelength conversion of high speed data signals", Electron. Lett., 29, (1993).

42. Y. Mori, "Dynamic properties of transverse-magnetic wave injected semiconductor lasers", IEEE J. Quantum Electronics, 27, 2415-2421 (1991).

43. Y. Mori, J. Shibata, T. Kajiwara, "Optical polarization bistability with high switching speed in a TM wave injected buried heterostructure laser", Appl. Phys. Lett., 51, 1971-1973 (1987).

44. Y. Mori, J. Shibata, T. Kajiwara, "Optical polarization bistability in TM wave injected semiconductor lasers", IEEE J. Quantum Electron., 25, 265-272 (1989).

45. Y. Mori, J. Shibata, T. Kajiwara, "Analysis of optical polarization bistability in transverse-magnetic-wave-injected semiconductor lasers", J. Appl. Phys., 67, 2223-2228 (1990).

46. Y. Mori, J. Shibata, Y. Sasai, H. Serizawa, T. Kajiwara, "Operation principle of the InGaAsP/InP laser transistor", Appl. Phys. Lett., 47, 649-651 (1985).

47. T. Mukai, K. Inoue, T. Saitoh, "Signal gain saturation in two-channel common amplification using a 1.5 μm InGaAsP travelling-wave laser amplifier", Electron. Lett., 23, 396-397 (1987).

48. T. Nakai, N. Ogasawara, R. Ito, "Optical bistability in a semiconductor laser amplifier", Japan J. Appl. Phys., 22, L310-L312 (1983).

49. K. Nonaka, H. Tsuda, H. Uenohara, H. Iwamura, T. Kurokawa, "Optical nonlinear characteristics of a side-injection light-controlled laser diode with a multiple-quantum-well saturable absorption region", IEEE Photon. Tech. Lett., 5, 139-141 (1993).

50. T. Odagawa, S. Yamakoshi, "Optical set-reset operations of bistable laser diode with single-wavelength light", Electron. Lett., 25, 1428-1429 (1989).

51. N. Ogasawara, R. Ito, "Static and dynamic properties of nonlinear semiconductor laser amplifiers", Japan J. Appl. Phys., 25, L739-L742 (1986).

52. Y. Ogawa, H. Ito, H. Inaba, "New bistable optical device using semiconductor laser diode", Japan J. Appl. Phys., 20, L646-L648 (1981).

53. M. Okada, H. Kikuchi, K. Takizawa, H. Fujikake, "The effects of a detuned optical input on bistable laser diodes with inhomogeneous current injection", IEEE J. Quantum Electron., 29, 109-120 (1993).

54. M. Okada, K. Takizawa, H. Kikuchi, H. Fujikake, "Undershooting and set-reset operation in bistable laser diodes with inhomogeneous excitation", IEEE J. Quantum Electron., 26, 850-857 (1990).

55. J. S. Perino, J. M. Wiesenfield, B. Glance, "Fibre transmission of 10 Gbit/s signals following wavelength conversion using a travelling-wave semiconductor optical amplifier", Electron. Lett., 30, 256-258 (1994).

56. H. Rokugawa, N. Fujimoto, T. Nakagami, "Error-free operation of wavelength conversion laser for photonic crossconnect node at 125Mbit/s", Electron. Lett., 27, 393-394 (1991).

57. G. Ropers, et al., "The inhibition mechanism in polarization bistable semiconductor lasers", IEEE J. Quantum Electron., QE-23, 1027-1032 (1987).

58. A. Sapia, P. Spano, B. Daino, "Polarization switching in semiconductor lasers driven via injection from an external radiation", Appl. Phys. Lett., 50, 57-59 (1987).

59. M. Schilling, et al., "6 THz range tunable 2.5 Gb/s frequency conversion by a multiquantum well Y laser", IEEE J. Quantum Electron., 29, 1835-1842 (1993).

60. W. F. Sharfin, M. Dagenais, "Dynamics of optically switched bistable diode laser amplifiers", IEEE J. Quantum Electron., QE-23, 303-308 (1987).

61. M. Shtaif, M. Horowitz, R. Nagar, G. Eisenstein, "An optically triggered oscillator based on wave coupling in a semiconductor optical amplifier", IEEE J. Quantum Electron., 30, 2188-2193 (1994).

62. M. A. Summerfield, J. P. R. Lacey, A. J. Lowery, R. S. Tucker, "All-optical TDM to WDM conversion in a semiconductor optical amplifier", Electron. Lett., 30, 255-256 (1994).

63. K. Takahata, K. Kasaya, H. Yasaka, Y. Kondo, M. Ikeda, "A unidirectional output optical frequency conversion devices with an asymmetric-k DBR structure", IEEE J. Quantum Electron., 30, 1219-1226 (1994).

64. M. C. Tatham, G. Sherlock, L. D. Westbrook, "20-nm optical wavelength conversion using nondegenerate four-wave mixing", IEEE Photon. Tech. Lett., 5, 1303-1306 (1993).

65. H. Tsuda, et al., "Wide range wavelength conversion experiments using a side-injection light-controlled bistable laser diode", Appl. Phys. Lett., 63, 3116-3118 (1993).

66. R. Vallee et al., "Mode description of the dynamical evolution of an acousto-optic bistable device", IEEE J. Quantum Electron., QE-21, 1423-1428 (1985).

67. N. A. Whitaker, H. Avramopoulos, P. M. W. French, M. C. Gabriel, R. E. LaMarche, "All-optical arbitrary demultiplexing at 2.5 Gbits/s with tolerance to timing jitter", Optics Lett., 16, 1838-1840 (1991).

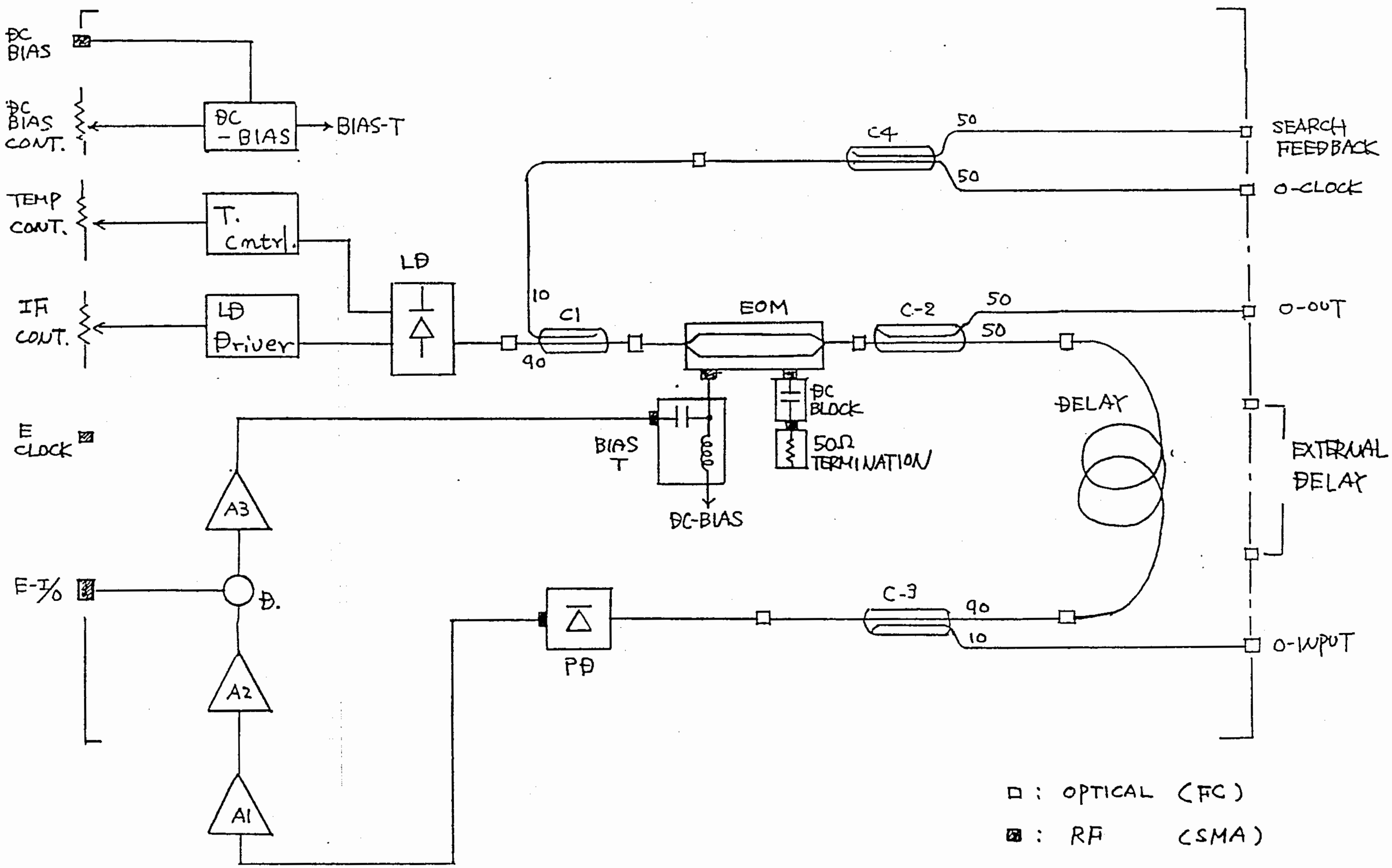
68. J. M. Wiesenfeld, B. Glance, J. S. Perino, A. H. Gnauck, "Wavelength conversion at 10 Gb/s using a semiconductor optical amplifier", IEEE Photon. Tech. Lett., 5, 1300-1303 (1993).

69. H. Yasaka, K. Takahata, K. Kasaya, K. Oe, "Frequency response of a unidirectional-output optical frequency conversion device with an asymmetrical-k DBR laser structure", IEEE Photon. Tech. Lett., 5, 1306-1310 (1993).

70. J. Zhou, N. Park, K. J. Vahala, M. A. Newkirk, B. I. Miller, "Efficiency of broadband four-wave mixing wavelength conversion using semiconductor traveling-wave amplifiers", IEEE Photon. Tech. Lett., 6, 50-52 (1994).

71. J. Zhou, N. Park, K. J. Vahala, M. A. Newkirk, B. I. Miller, "Four-wave mixing wavelength conversion efficiency in semiconductor traveling-wave amplifiers measured to 65 nm of wavelength shift", IEEE Photon. Tech. Lett., 6, 984-987 (1994).

# List of Figures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C-2
50
50
C4
50
50
SEARCH FEEDBACK
O-CLOCK
O-OUT
DC BLOCK
50Ω TERMINATION
BIAS T
DC-BIAS
DELAY
EXTERNAL DELAY
E CLOCK
A3
E-I/O
D.
A2
A1
PD
C-3
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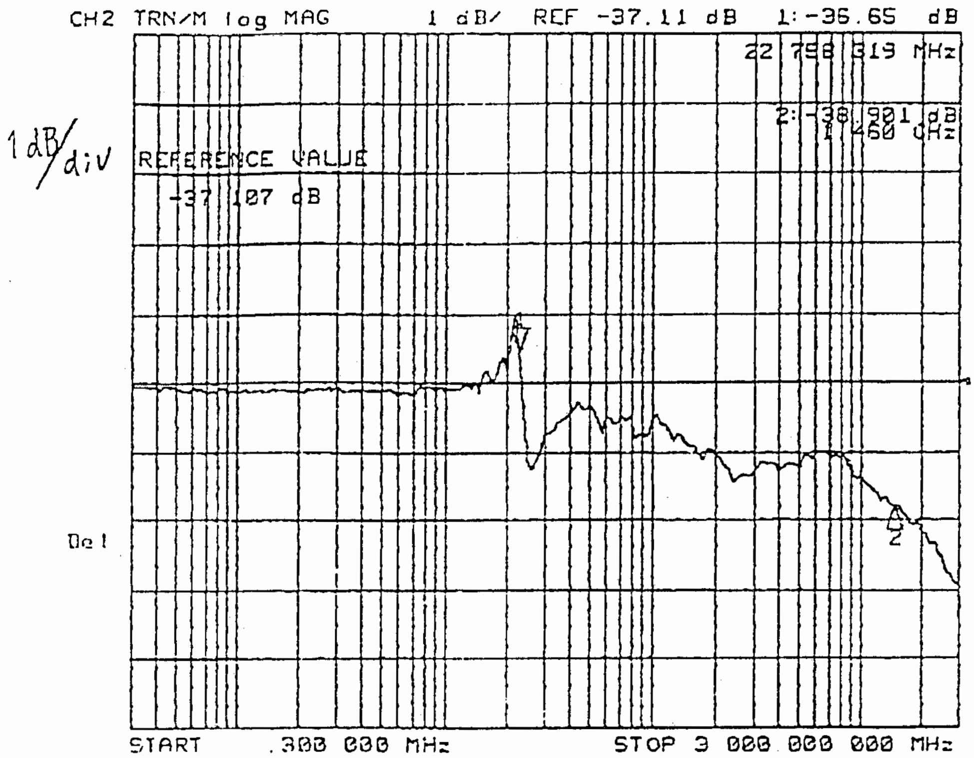
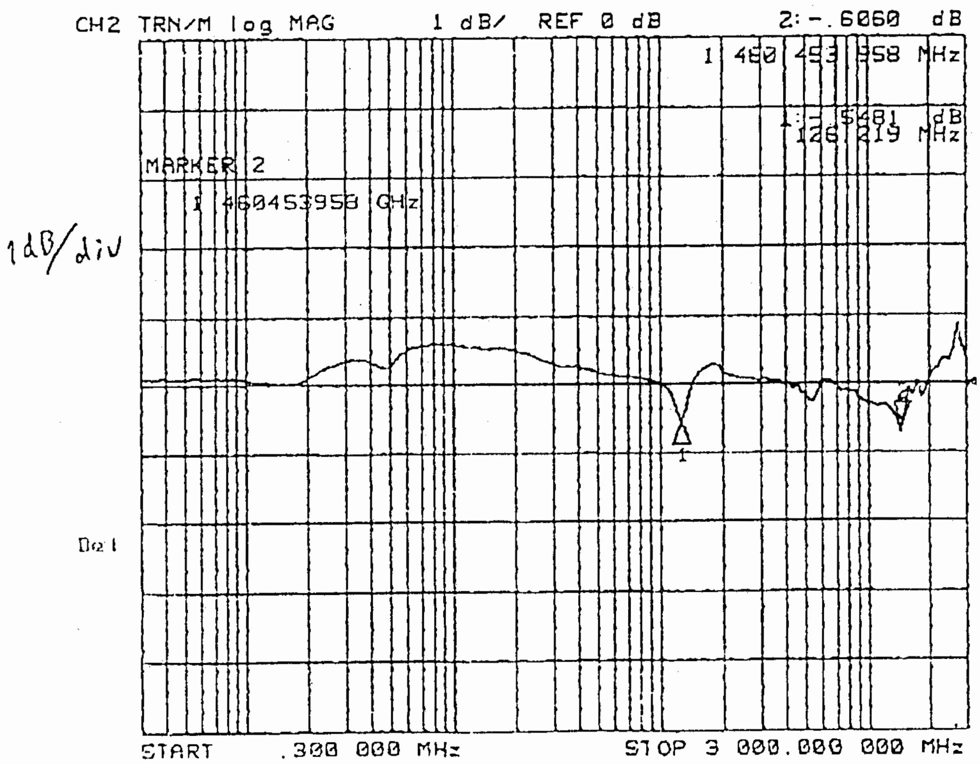
O-INPUT
□ : OPTICAL (FC)
▣ : RF (SMA)

Fig. 1

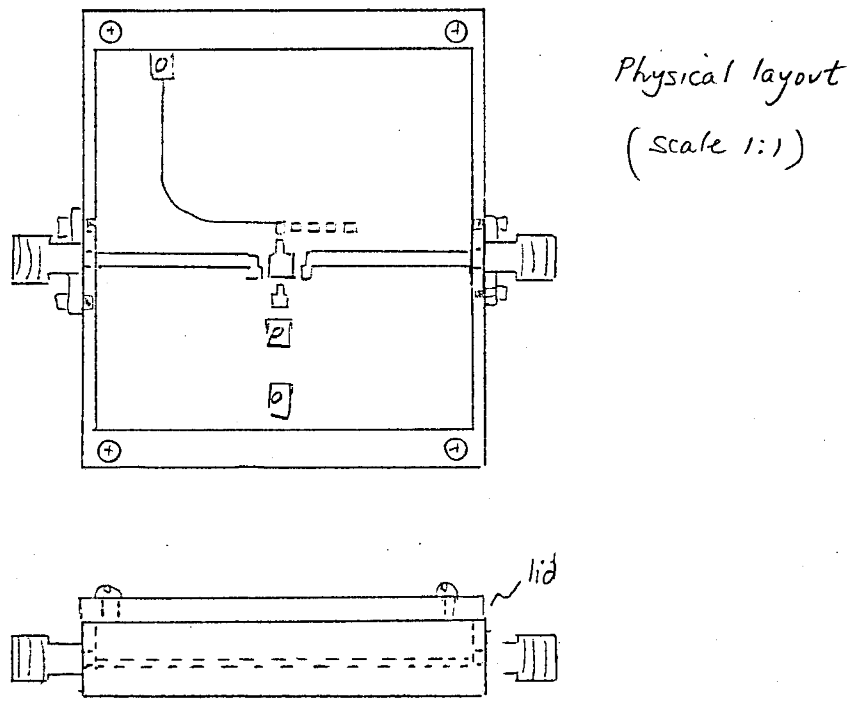


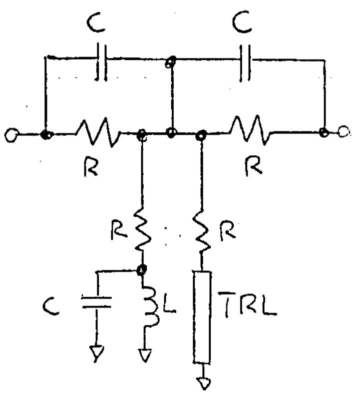

(a) Modulator/Photodetector



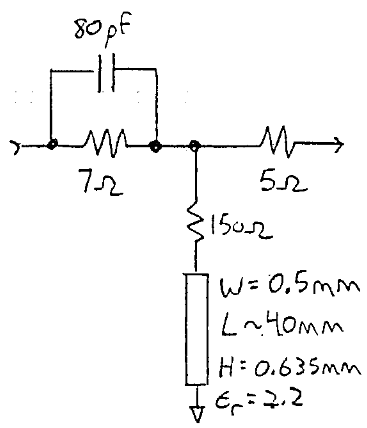

(b) Single Amplifier

Fig. 2




General purpose equalizer




Initial design

Fig. 3 (a)

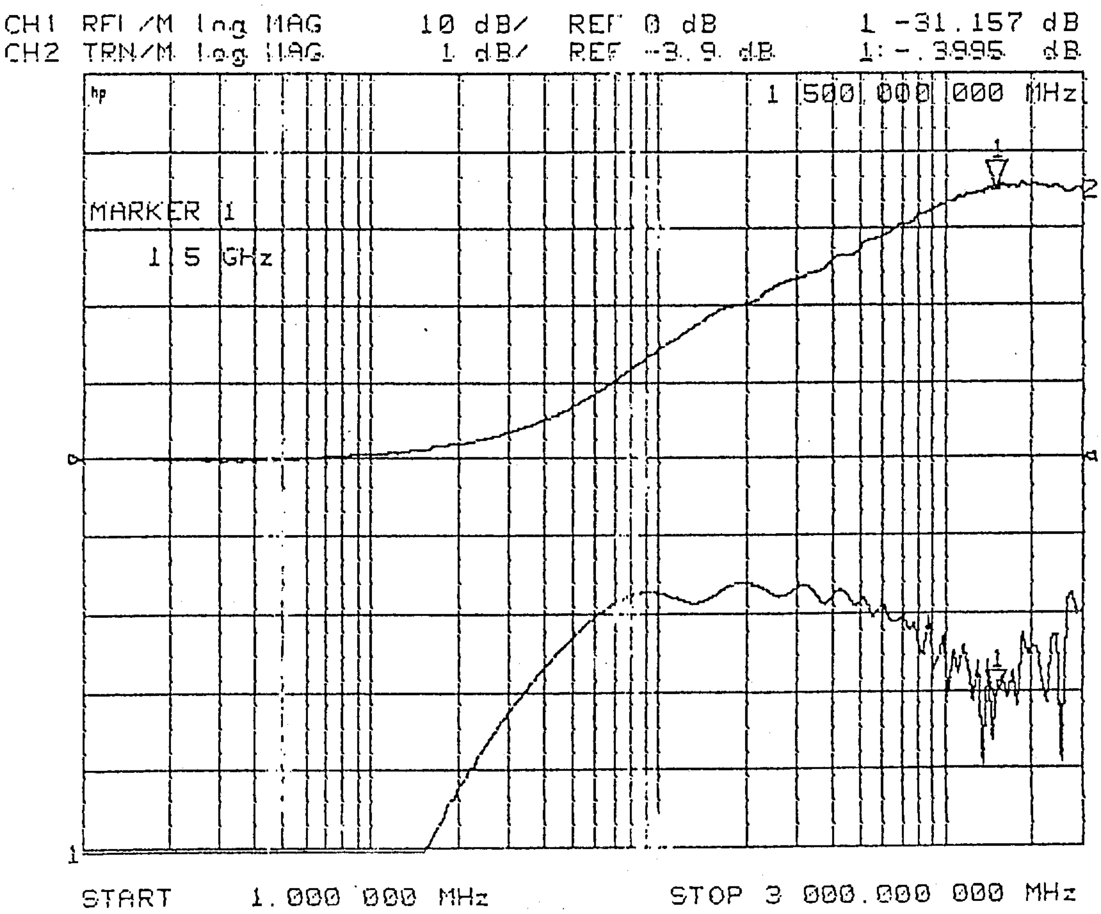

CH1 RFL/M log MAG 10 dB/ REF 0 dB 1 -31.157 dB
CH2 TRN/M log MAG 1 dB/ REF -3.9 dB 1: -.3995 dB
1 500 000 000 MHz
MARKER 1
1.5 GHz
START 1.000 000 MHz
STOP 3 000.000 000 MHz

Fig. 3(b)

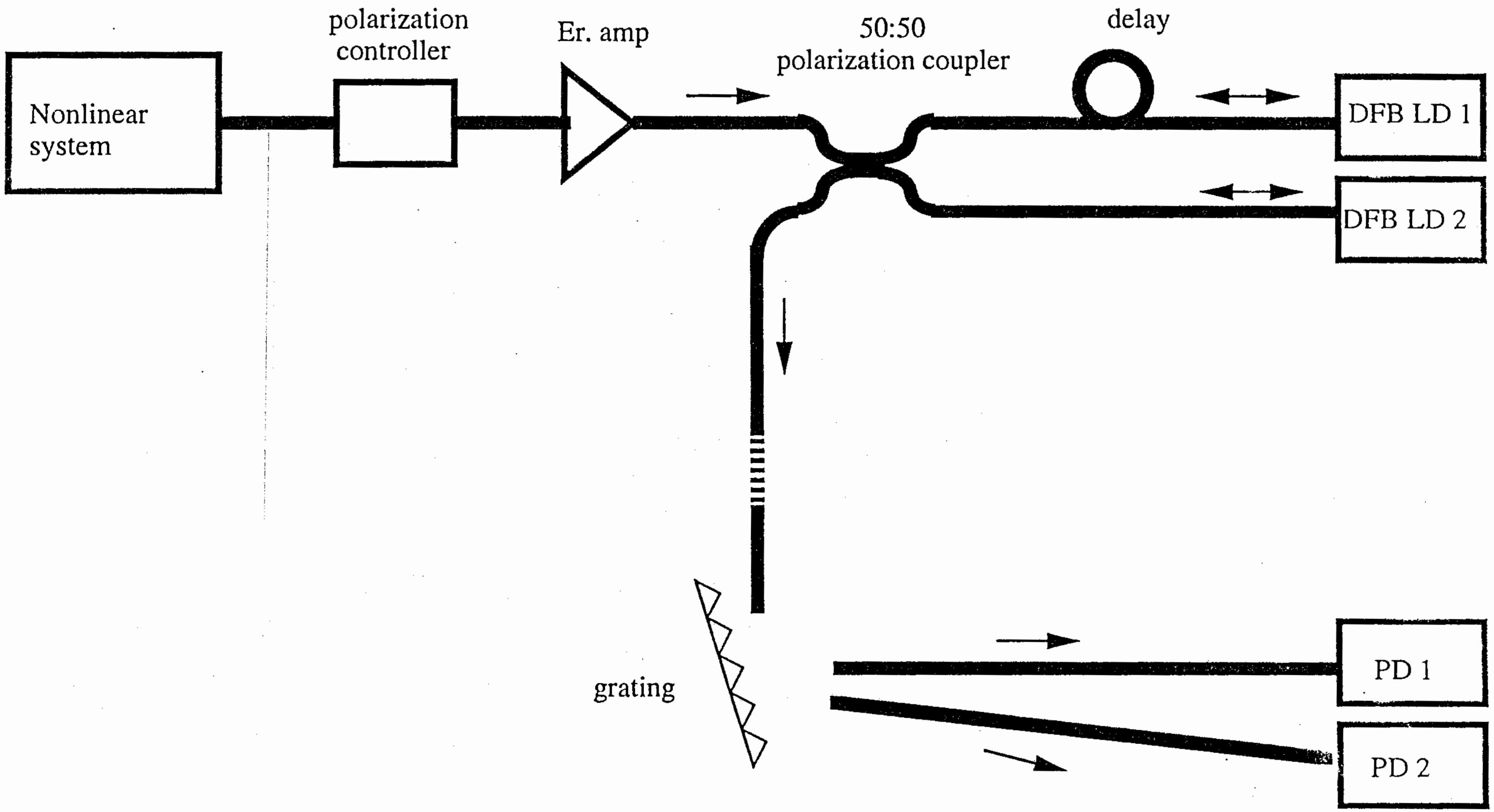

polarization
controller
Er. amp
50:50
polarization coupler
delay
Nonlinear
system
DFB LD 1
DFB LD 2
grating
PD 1
PD 2

Fig. 4

(a)

(b)

(c)

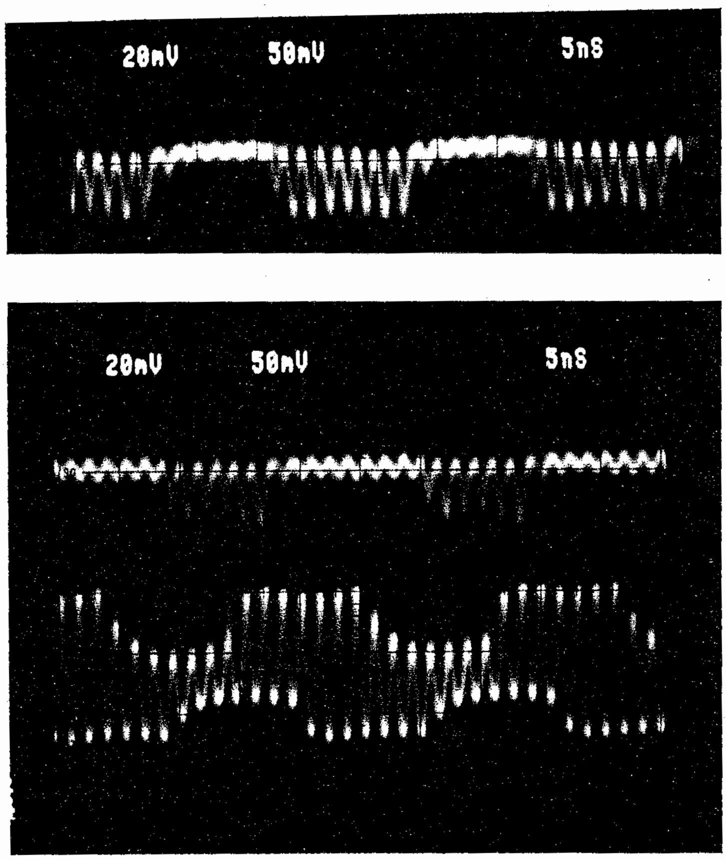



Fig. 5

(a)

(b)

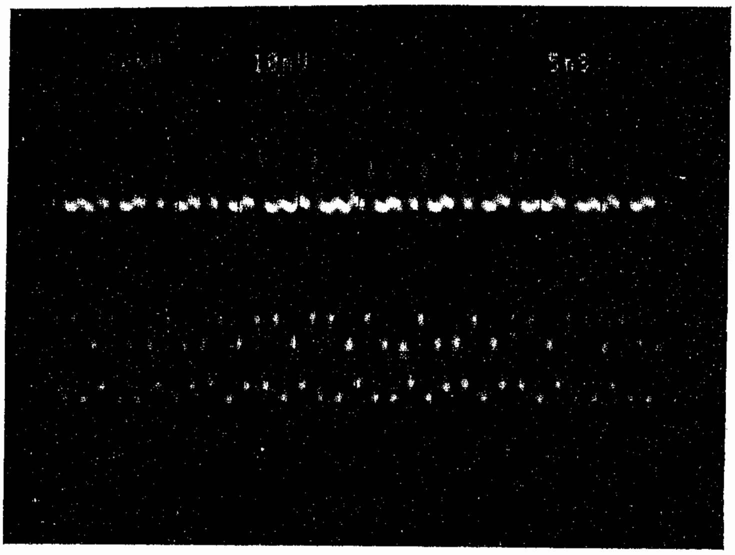



Fig. 6