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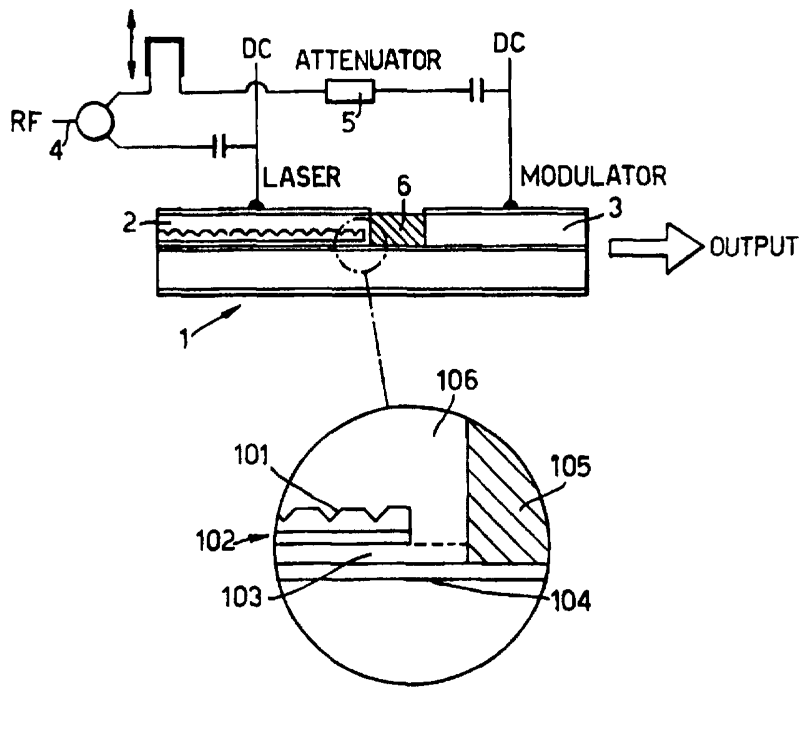
(54) Title: OPTICAL TRANSMITTER



(57) Abstract

An optical transmitter (1) includes a directly modulated semiconductor laser (2) and a non-linear optical intensity modulator (3) which is connected in series with the output of the laser. High frequency analogue modulating signals are applied both to the laser and to the modulator. The modulator has a transfer characteristic such that it cancels intermodulation distortion in the output from the laser, to give a source with an improved dynamic range. The transmitter is suitable for use in an analogue optical distribution system for cellular radio.

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OPTICAL TRANSMITTER

The present invention relates to an optical transmitter, and in particular to a transmitter suitable for use in the transmission and distribution of analogue optical signals modulated at RF or microwave frequencies. The low losses and EMI immunity associated with optical fibres, makes their use an attractive proposition, for example, in the distribution of signals to remote transmitter sites in a cellular radio system. The optical transmitters used hitherto with such optical fibre links have either been in the form of directly modulated laser diodes, or have comprised continuous wave lasers coupled with a separate electro-optic modulator such as a Mach-Zehnder intensity modulator or an electroabsorption modulator. Such optical transmitters suffer however, from a dynamic range which is significantly inferior to that of the electronic devices commonly used in cellular base stations. This has restricted the use of optical analogue links.

For a given received optical power, the dynamic range of analogue optical-fibre links is limited primarily by the linearity of the electrical to optical transfer characteristic of the optical transmitter. It has previously been proposed to use schemes such as electrical pre-distortion or optical feed-forward linearisation to increase the overall system dynamic range. It would be desirable however to improve the intrinsic source linearity. In the context of a source using a continuous wave laser followed by a Mach-Zehnder modulator, it has been proposed to use two modulators in cascade in order to improve linearity [Betts. G.E. IEEE Trans. Microwave Theory & Techniques, vol 42 no. 12 pp 2642-2649]. By feeding an RF drive signal to both modulators in a prescribed ratio, the second modulator corrects for the distortion of the first.

According to a first aspect of the present invention, there is provided an optical transmitter comprising:

a) a directly modulated semiconductor laser including an input for a high frequency analogue electrical modulating signal; and

b) a non-linear optical intensity modulator which is connected in series with the optical output of the laser and which includes an input for a high frequency analogue electrical modulating signal corresponding to the signal applied to the laser, the modulator having a transfer characteristic arranged to cancel at least partially intermodulation distortion in the optical signal output by the laser.

The present invention provides a directly modulated laser source with an intrinsically improved linearity. This achieved by using a modulator following the directly modulated laser having distortion characteristics which tend to cancel the distortion produced by the laser.

Preferably the modulator is an electroabsorption modulator preferably integrated with the semiconductor laser. Preferably the laser is a multi-quantum well (MQW) distributed feedback (DFB) laser, and the modulator is an MQW electroabsorption modulator.

The preferred implementation of the present invention uses monolithically integrated components which together form a compact, single-chip linearised analogue source. This arrangement offers superior RF phase stability by comparison with implementations using discrete devices. Furthermore, the non-linearity of electro absorption modulators is highly controllable, making them ideal for the task of linearising a DFB laser.

Alternatively, the electro-optic modulator may be a Mach-Zehnder device which may be a planar device.

The modulator may have a predetermined characteristic chosen to be complementary to the expected characteristics of the modulated source. Preferably however the modulator is actively controlled to linearise the output signal. Preferably the system comprises a detector for monitoring the output of the transmitter, and means for supplying a control input to the modulator dependent on the output of the detector. The detector may be arranged to detect, for example, the third harmonic of the output signal, and to drive the modulator in a feedback loop to minimise this output.

Systems embodying the present invention will now be described in further detail, by way of example only, with reference to the accompanying figures in which:-

Figure 1 is a schematic of a laser/EA modulator embodying the present invention;

Figure 2 is a graph showing the transmission characteristic of the modulator of Figure 1;

Figures 3a and 3b are spectra detecting the output of the device of Figure 1;

Figure 4 is a graph showing the dependence of distortion on input RF power;

Figures 5a and 5b are schematics showing in further detail the circuits embodying the present invention;

Figure 6 is a cross-section showing in detail the laser/modulator of Figure 1;

Figure 7 shows the crystal structure used in the fabrication of the device of Figure 1;

Figure 8 is a schematic of an alternative embodiment; and

Figure 9 is a diagram showing a cellular radio system incorporating an optical transmitter embodying the present invention.

An optical transmitter 1 comprises a directly modulated semiconductor laser 2 and an optical intensity modulator 3 connected in series with the optical output of the laser. An RF source 4 generates a modulating voltage which is superimposed on a dc bias applied to the laser and to the modulator. An attenuator 5 connected in series between the RF source and the gate of the modulator 3 is used to set a predetermined ratio between the amplitude of the modulating signal applied to the modulator and that applied to the laser. The modulator has a transfer characteristic which, for small signals over a selected range of bias voltages is generally complementary to that of the laser, and so is able to cancel intermodulation distortion generated by the laser.

The enlarged detail shows a grating layer 101, MQW active layer 102, n-InP spacer layer 103, electroabsorption layer 104, Fe InP region 105 and p InP region 106.

In the present example, the transmitter comprises an integrated DFB laser/EA modulator, as shown schematically in Figure 1. It has a 395 μm long InGaAs/InGaAsP MQW DFB laser section and a 190 μm long InGaAsP/InGaAsP MQW EA modulator section separated by a 100 μm passive waveguide section 6. Modulator and laser epitaxial layers were grown sequentially, separated by a 0.2 μmInP spacer layer, by MOVPE. The laser epi-layers were selectively removed from above the modulator and passive waveguide sections and mesas etched prior to the growth of a high resistivity Fe-doped, InP layer providing current blocking and isolation between the sections. The finished chip is packaged in a 14-pin high speed connectorised module with welded-in lens-ended fibre. Measured CW side mode suppression ratio was > 40 dB and electrical isolation between the DFB and EA modulator sections was 2 MΩ. The DC modulator transmission characteristic (normalised to 0V) is shown in Figure 2 as a function of the modulator reverse bias.

The cross-section of the device is shown in further detail in Figure 6, and the crystal structure used in the fabrication of the device is shown in Figure 7. It consists of the layers necessary to make a DFB laser grown on top of the layers necessary to form an EA modulator. The growth technique used, as noted above, is MOVPE. Post growth analysis showed that the peak photoluminescence wavelength of the absorber layer was 1.5μm, as required. In fabricating the device, second order gratings with quarter wavelength phase shifts are formed on the sample using electron-beam lithography. The device is then formed with steps of photolithography and overgrowth. An economy of process steps is achieved by designing the laser and modulator sections to be buried heterostructures with Fe-doped InP current blocking structures, thus enabling them to share mesa definition, Fe-doped InP overgrowth, P-contact layers overgrowth and metallisation stages. An additional photolithography step is needed to remove the laser layers from the modulator and passive sections prior to mesa definition. An overgrowth step involves the deposition of 1 μm of Fe-doped InP in the passive region to electrically isolate the laser and modulator sections. This is carried out after the P-contact lasers are removed from everywhere except above the active stripe in the laser and modulator regions.

In this example the width of the absorber layer in the modulator section was estimated from SEM (scanning electron microscope) analysis to be 1.7 μm. The slice was thinned to 90 μm. Bars were cleaved off and coated with multi-layer anti-reflection coatings at both facets, before being scribed up into individual chips for characterisation and packaging.

In the final packaged form of the transmitter, the chip sits p-side up on a metallised diamond. A low impedance path is provided from the diamond to the ground plane of the package which serves as the negative electrical terminal of the

DFB and the positive terminal of the reverse-biased modulator. The package incorporates a thermistor and a Peltier cooler so that the chip temperature can be controlled. A wide bandwidth (40 GHz) K-type connector is used to provide a high speed electrical contact to the p-side of the modulator. A dc electrical contact is made to the p-side of the DFB. To measure the performance of the transmitter, a photodiode is placed near the DFB facet to enable the laser output to be monitored directly.

Figures 3a and 3b illustrate the performance of the transmitter. Standard two-tone tests were carried out on the laser-EA modulator device at RF frequencies relevant to fibre-fed GSM cellular radio (centre frequency around 950 MHz, carrier separation equal to 200kHz). A power divider was used to split the RF between the laser and the modulator, the latter being fed via the attenuator 5 and a phase adjuster.

The detected spectrum with RF applied to the laser only, is shown in Figure 3a for a modulator bias of -1.21 V. Initial adjustments to the fixed attenuator (coarse) and modulator bias (fine) were made, with RF to the modulator section only, so that the third and fifth-order intermodulation products were approximately the same amplitude as those with the RF applied to the laser only, but with a much lower detected signal level. Following this, with the RF applied to both devices, the modulator bias was optimised to achieve maximum distortion cancellation. The detected spectrum of Figure 3b shows clearly the cancellation of both third and fifth-order intermodulation products when the bias is optimised, yet the detected carrier level is within 1 dB of that measured without distortion cancellation.

More than one combination of attenuator and bias voltage resulted in distortion cancellation. In a further example, a bias of -0.12 V was applied to the modulator and an attenuation ratio of 26 dB used. Again cancellation of the intermodulation products was achieved. Figure 4 shows the dependence of the third order intermodulation distortion with input RF power for this modulator bias of -0.12 V with and without the RF applied to the modulator. The receiver in this case was a simple pin photodiode terminated with 50Ω. The photo current in this measurement was 0.9 mA giving a shot-noise dominated noise floor of -167 dB.Hz. Distortion cancellation results in an improvement of the spurious-free dynamic range (SFDR) from 96 $dB.Hz^{2/3}$ to 117 $dB.Hz^{6/7}$.

Figures 5a and 5b show in further detail the two configurations used to obtain the results discussed above. In these circuits, drive signals are combined in a power combiner 51 and passed through an amplifier 52. The resulting signal is split by a 3dB coupler 53. One part of the signal is then coupled into the drive to the laser diode 54. The dc bias current i_{dc} is 154mA. The other part of the signal passes through a 20dB attenuator and a control stage 55 and is coupled to the control input of the electro-optic modulator. In the case of Figure 5a, a further attenuator 56 is included in the signal path to the modulator 57. The control stage 55 may comprise a microwave phase adjuster to adjust the phase of the drive to the modulator to match that of the drive to the laser. In this example, the stage comprises a pair of microwave strip lines which are moved relative to each other to provide the required phase change. In addition, as shown schematically in Figure 9, feedback from the optical output of the transmitter may be used to control the bias applied to the modulator. To facilitate this, two rf tones may be added resistively to the drive signal. An optical coupler at the output of the transmitter is then used to split off a small fraction of the output power. This is filtered to select the difference frequency of the two rf tones, passed through a rectification diode and amplified to produce a control signal for the modulator at an appropriate level.

Figure 8 shows an alternative embodiment, in which the electro-optic modulator is a Mach-Zehnder planar device available commercially as GEC Advanced Optical Products Y-35-8931-02. A directly modulated DFB semiconductor laser was used as the optical source.

As noted above, the transmitter of the present invention is particularly suitable for use in an analogue optical link within a cellular radio system. Figure 9 illustrates such a system a transmitter such as that illustrated in Figure 1 is located in a central station 91 linked to a number of GSM cellular base stations 92 by optical fibre links 93 (for ease of illustration a single link and base station are shown in the figure) . At the cellular base station, the optical RF carrier signal is converted to an electrical RF signal for transmission to mobile stations 94. This may be done, for example, using the techniques disclosed in the paper by

H.Ogawa, Trans. on Microwave Theory and Techniques, Vol.39, No.12, Dec 1991, pp 2045-2051.

TABLE 1

LAYER	MATERIAL	THICKNESS
A: Substrate	n InP S-doped $1x10^{18}cm^{-3}$	300μm
B: Buffer layer	n InP S-doped $1x10^{18}cm^{-3}$	3μm
C: Confinement layer	Q1.10 undoped 200Å thick	total of 0.215μm with layer D
D: MQW absorber layer	13 periods of undoped Q1.59 wells 95Å thick and undoped Q1.10 barriers 55Å thick	total of 0.215μm with layer C
E: Spacer layer	n InP S-doped $1x10^{16}cm^{-3}$	0.2μm
F: Confinement layer	Q1.30 undoped 100Å thick	total of 0.138μm with layer G
G: MQW gain layer	8 periods of undoped ternary wells 80Å thick and undoped Q1.30 barriers 80Å thick	total of 0.138μm with layer F
H: Grating layer	p Q1.10 Zn-doped $5x10^{17}cm^{-3}$	0.2μm
I: Cap layer	p InP Zn-doped $5x10^{17}cm^{-3}$	0.05μm

CLAIMS

1. An optical transmitter comprising:

a) a directly modulated semiconductor laser including an input for a high frequency analogue electrical modulating signal; and

b) a non-linear optical intensity modulator which is connected in series with the optical output of the laser and which includes an input for a high frequency analogue electrical modulating signal corresponding to the signal applied to the laser, the modulator having a transfer characteristic arranged to cancel at least partially intermodulation distortion in the optical signal output by the laser.

2. A transmitter according to claim 1, in which the modulator is an electroabsorption modulator.

3. A transmitter according to claim 2, in which the electroabsorption modulator is integrated with the semiconductor laser.

4. A transmitter according to any one of the preceding claims, in which the laser is a DFB laser.

5. A transmitter according to claim 4, in which the laser is a multi-quantum well (MQW) distributed feedback (DFB) laser and the modulator is an MQW electroabsorption modulator.

6. A transmitter according to any one of claims 1 to 4, in which the modulator is a Mach-Zehnder device.

7. A transmitter according to any one of the preceding claims, further comprising a control circuit for actively controlling the modulator to linearise the optical output signal.

8. A transmitter according to claim 7, in which the said control circuit comprises a detector for monitoring the output of the transmitter, and the output

of the control circuit is connected to a control input to the modulator and in use applies to the control input a control signal which depends on the output of the detector.

9. A cellular radio system including an analogue optical link between a central station and a remote base station, in which the central station includes an optical transmitter according to any one of the preceding claims arranged to generate a modulated optical signal for transmission on the analogue optical link.

10. A method of generating a high frequency analogue optical signal comprising applying a high frequency analogue electrical modulating signal to a semi-conductor laser, applying a corresponding high frequency analogue electrical modulating signal to a non-linear electro-optic modulator connected in series with the optical output of the laser, the modulator having a transfer characteristic arranged to cancel at least partially intermodulation distortion in the optical signal output by the laser.

11. A method according to claim 10, further comprising actively controlling the modulator and thereby linearizing the optical signal.

12. A method according to claim 11, in which the step of actively controlling includes:

i) detecting an optical output of the transmitter; and

ii) varying in dependence upon the said optical output a control input which is applied to the modulator.

13. A method of operating a cellular radio system comprising:

a) at a central station, generating a high frequency analogue optical signal by a method according to any one of claims 10 to 12;

b) transmitting the said optical signal over a analogue optical link to a remote base station; and

c) subsequently deriving from the sald optical signal a radio frequency signal in the electrical domain for radio transmission from the remote base station.

Fig. 1.

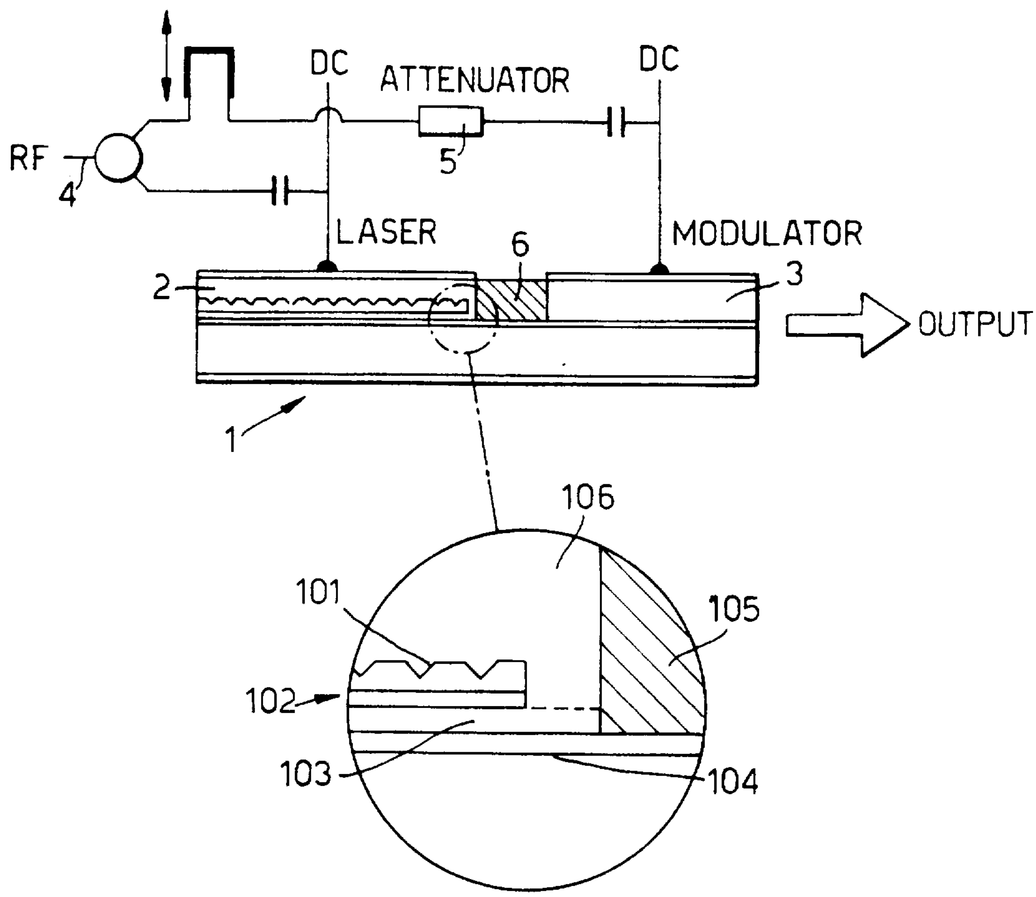

DC
ATTENUATOR
DC
RF
4
5
LASER
6
MODULATOR
2
3
OUTPUT
1
106
101
105
102
103
104

Fig.2.

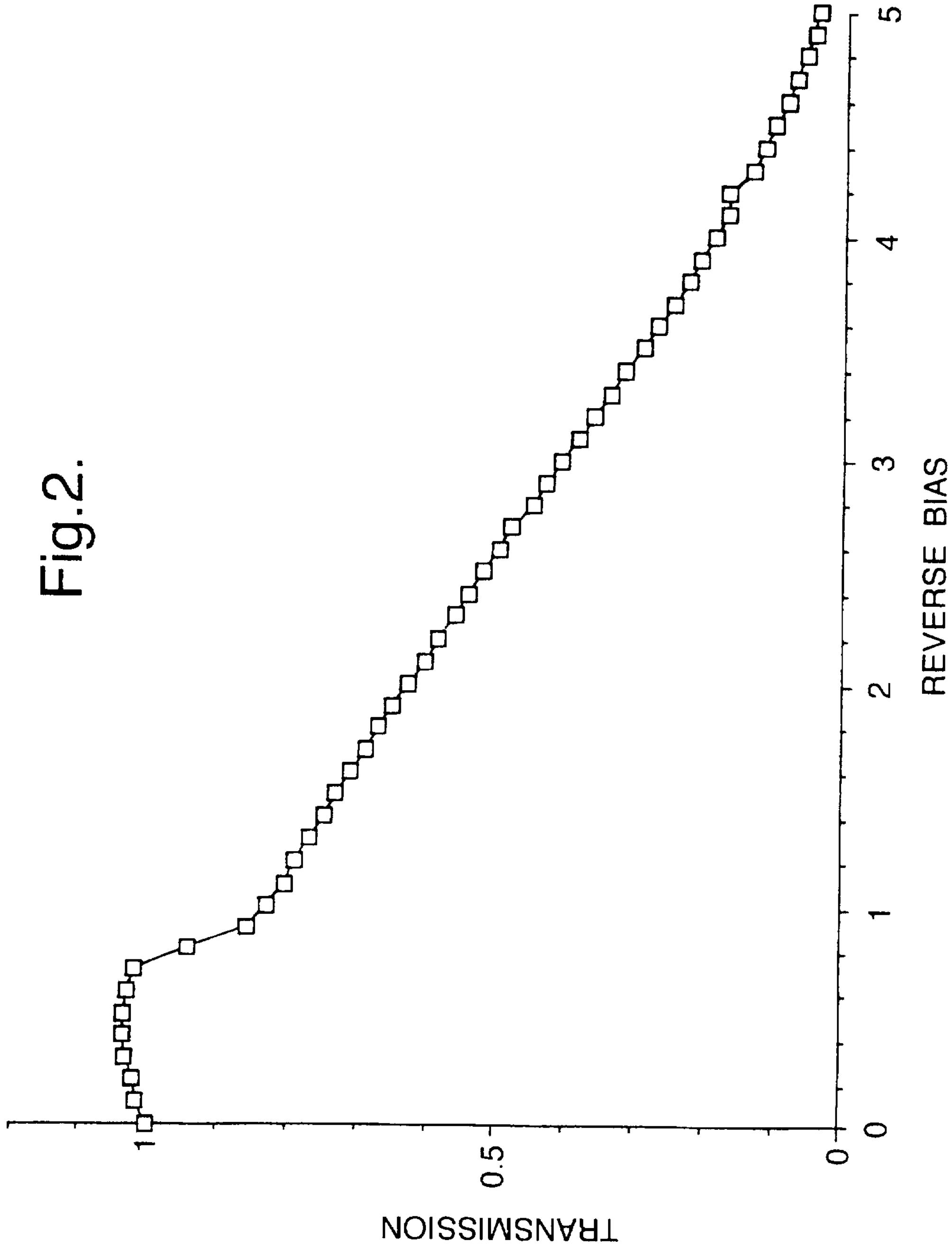
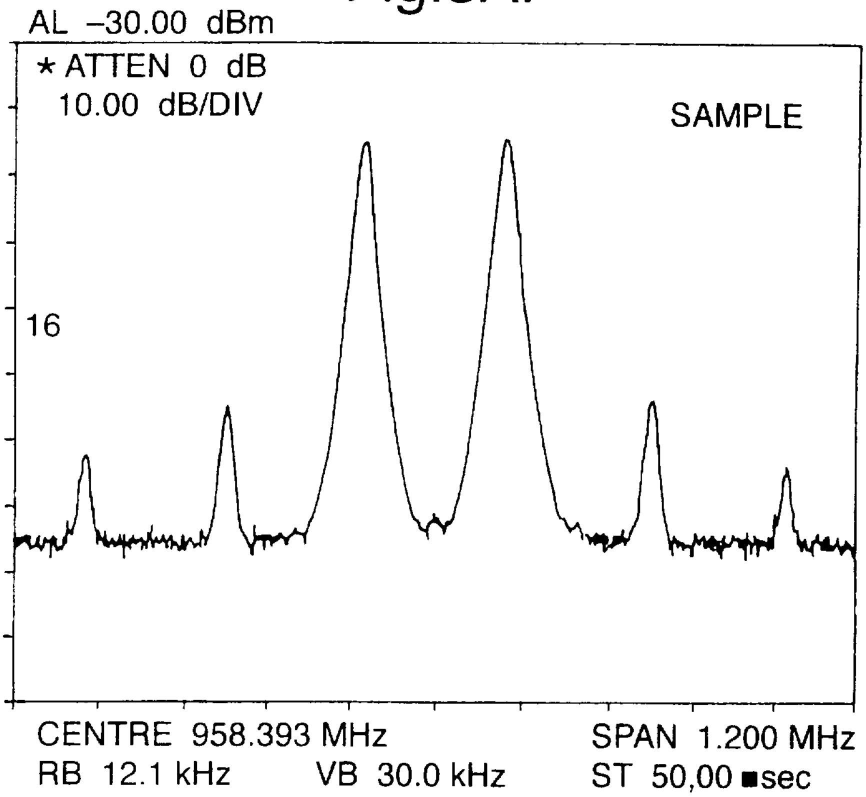


Fig.3A.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10.00 dB/DIV
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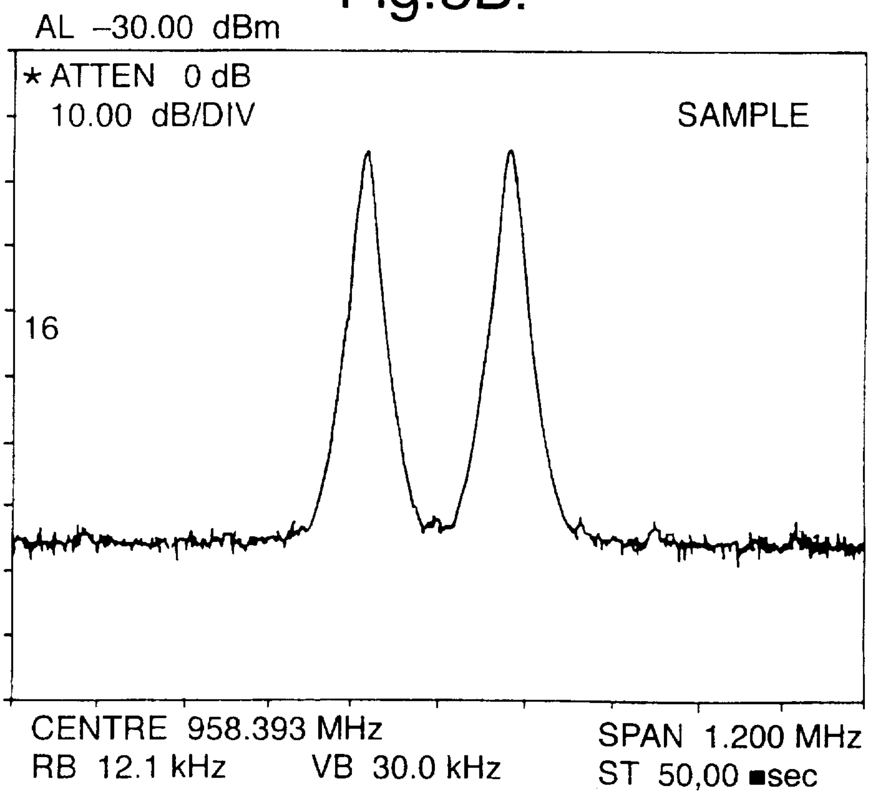
ST 50,00 ■sec

Fig.3B.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* ATTEN 0 dB
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CENTRE 958.393 MHz
SPAN 1.200 MHz
RB 12.1 kHz
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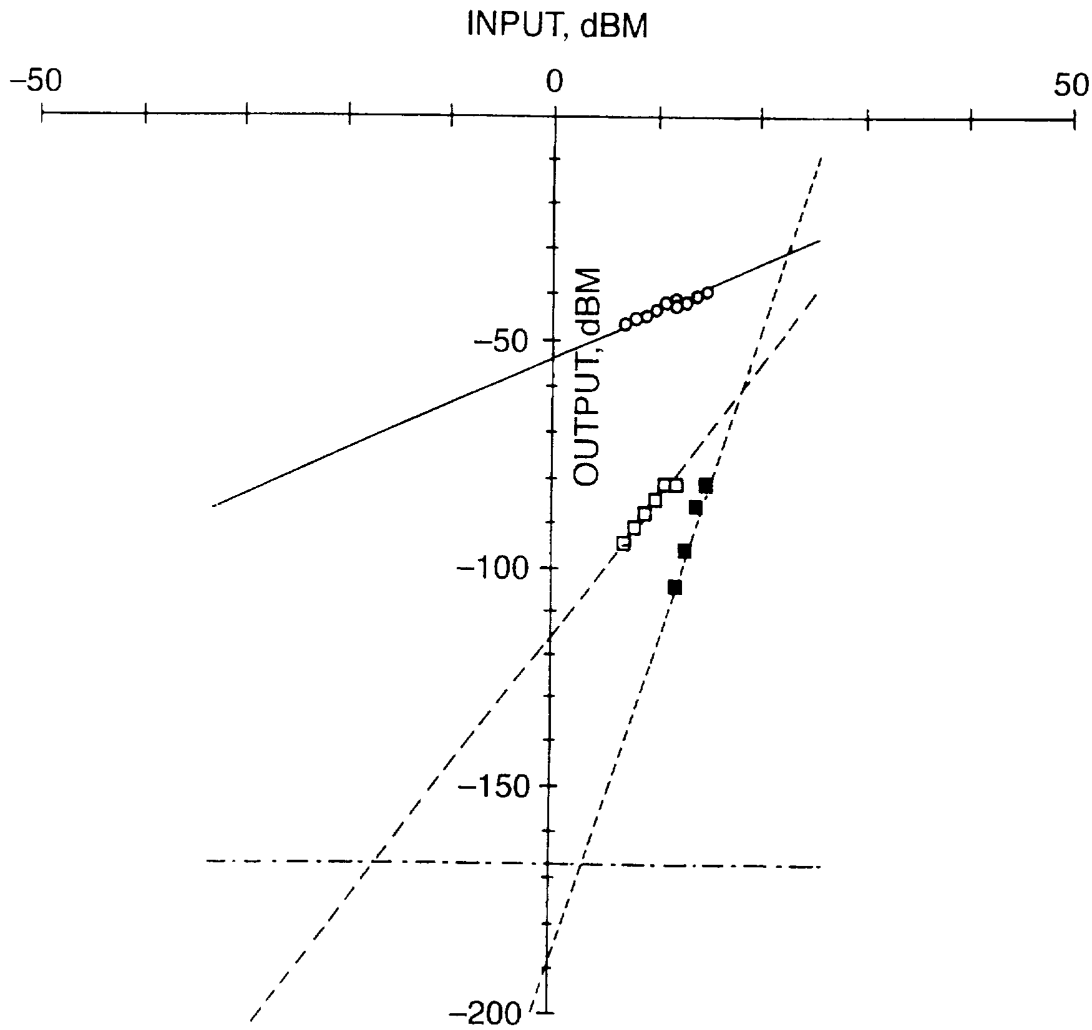
ST 50,00 ■sec

Fig.4.



CONDITION 1

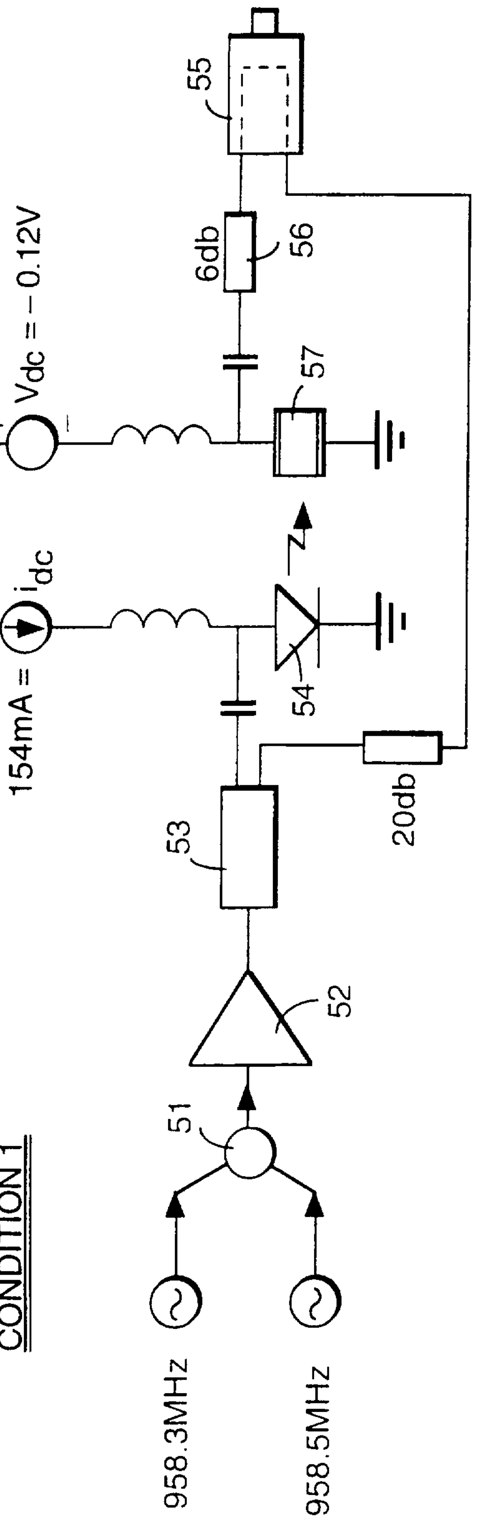


Fig.5a.

CONDITION 2

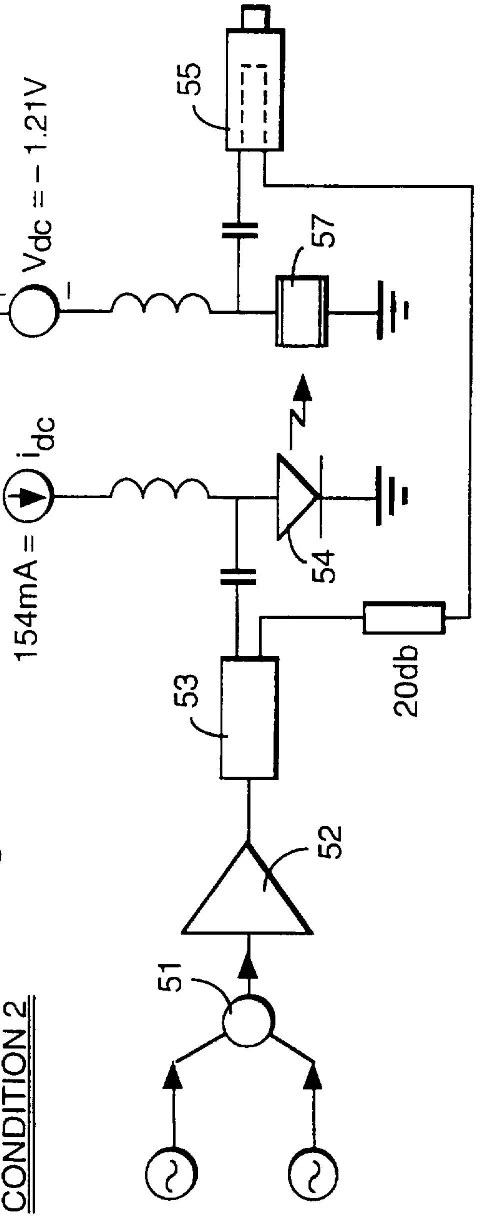
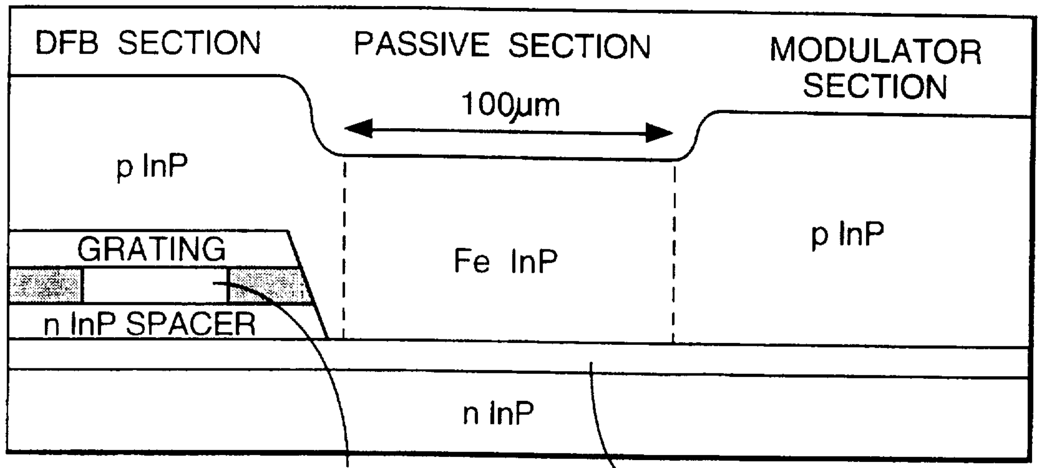


Fig.5b.

Fig.6.


DFB SECTION
PASSIVE SECTION
MODULATOR SECTION
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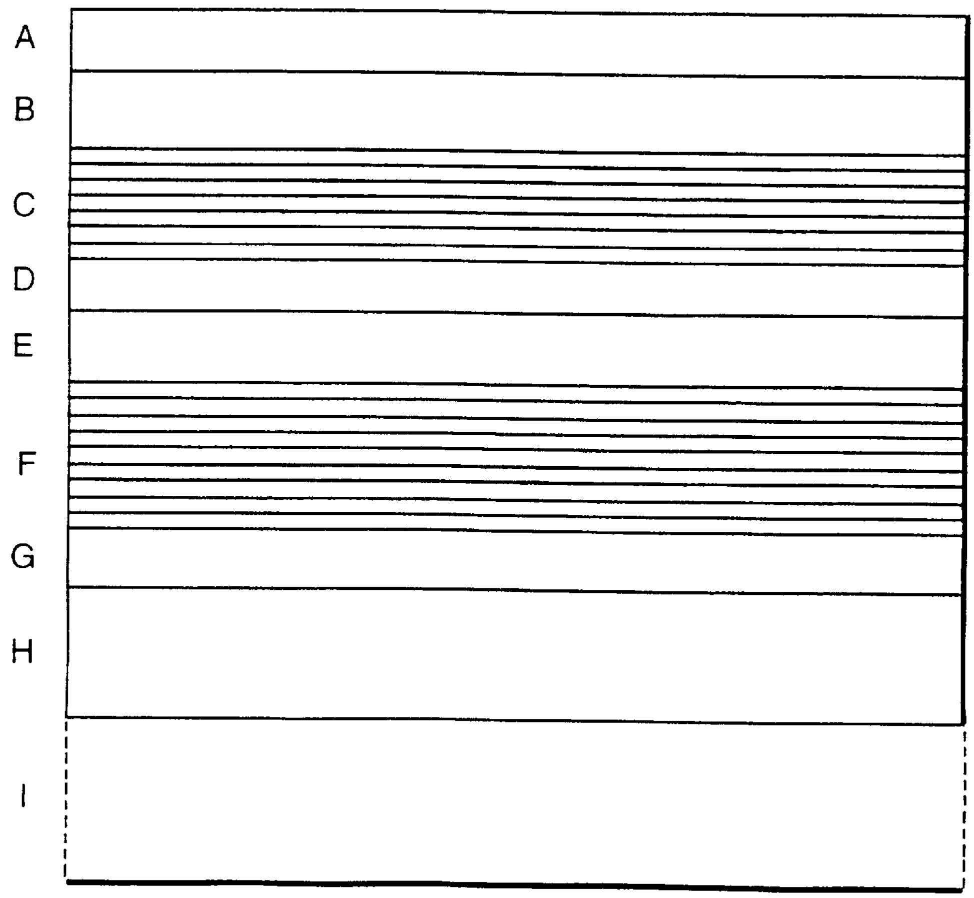
GRATING
Fe InP
p InP
n InP SPACER
n InP
MQW GAIN
MQW ABSORBER

Fig.7.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B
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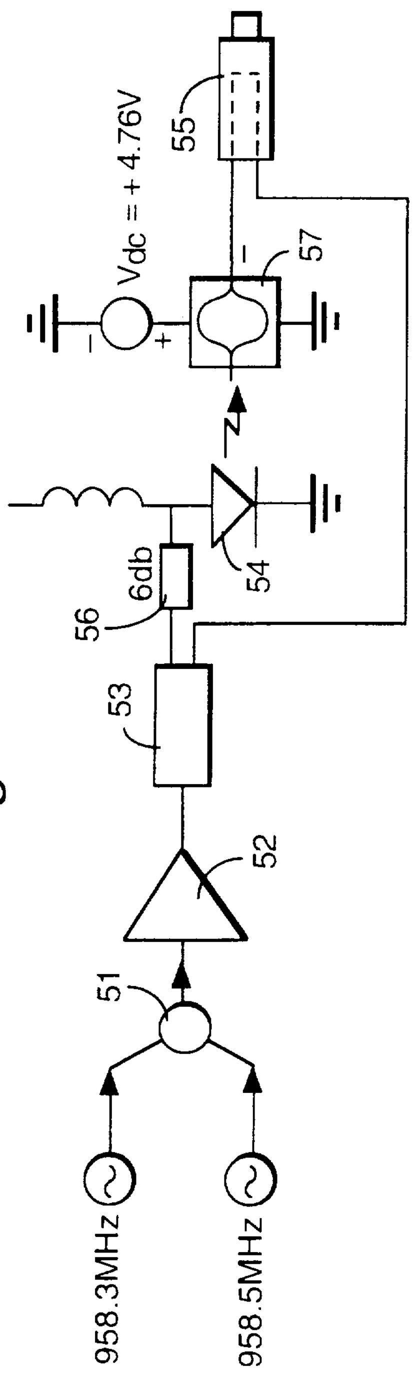
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958.5MHz
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52
53
56
6db
54
55
Vdc = + 4.76V
57

Fig.8.

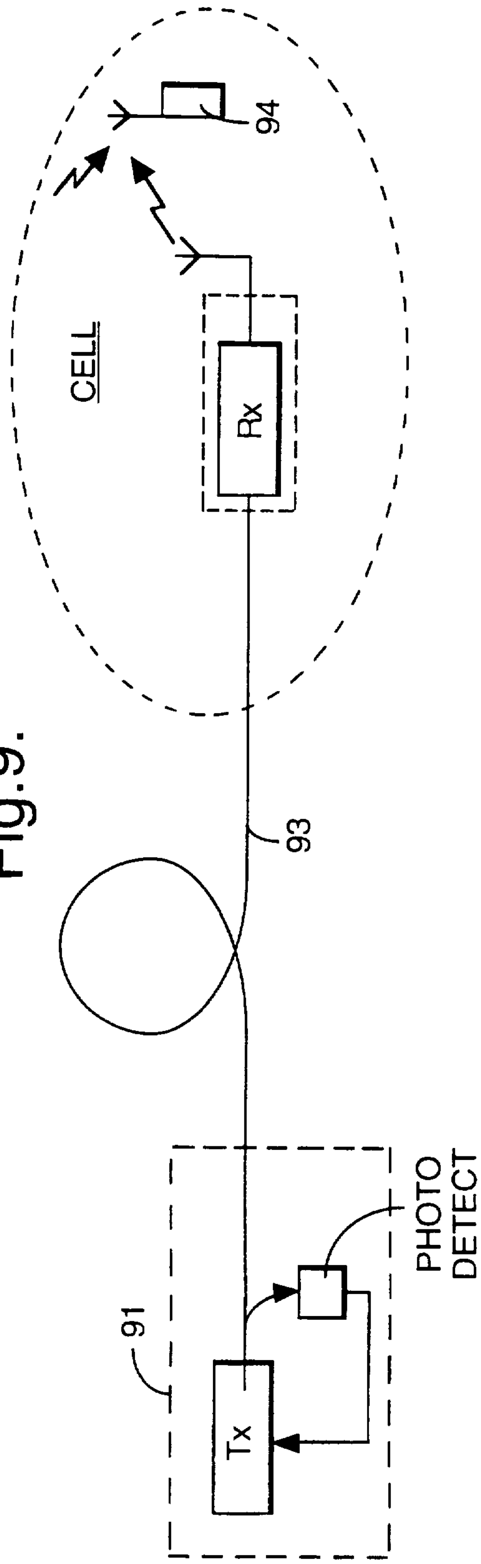
CELL
Rx
94
93
91
Tx
PHOTO DETECT

Fig.9.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 96/02855

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04B10/18 H01S3/025 G02F1/015

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04B H01S G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 484 791 A (GENERAL INSTRUMENT CORPORATION) 13 May 1992 see page 2, line 20 - page 3, line 24 see page 5, line 1 - line 35 ---	1,2,6,10
A	IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 7, no. 10, October 1995, NEW YORK US, pages 1154-1156, XP002014851 G.C. WILSON ET AL.: "INTEGRATED ELECTROABSORPTION MODULATOR/DBR LASER LINEARIZED BY RF CURRENT MODULATION" see the whole document ---	1-3,5,7,10

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[X] Further documents are listed in the continuation of box C.

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1

Date of the actual completion of the international search	Date of mailing of the international search report
29 January 1997	05.02.97

Name and mailing address of the ISA	Authorized officer
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 407 919 A (HARMONIC LIGHTWAVES, INC.) 16 January 1991 see abstract see page 4, line 52 - page 5, line 51 see page 6, line 30 - page 9, line 6; figure 8	1-4,6-8, 10-12
A	EP 0 493 817 A (GTE LABORATORIE INCORPORATED) 8 July 1992 see abstract see column 2, line 5 - column 4, line 9	1,6,10
A	US 5 166 509 A (M.E. CURRAN) 24 November 1992 see column 1, line 47 - column 2, line 34 see column 2, line 53 - column 4, line 45; figure 1	1,2,7,8, 10-12
A	JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 13, no. 8, August 1995, NEW YORK US, pages 1606-1612, XP000537116 T. IWAI ET AL.: "SIGNAL DISTORTION AND NOISE IN AM-SCM TRANSMISSION SYSTEMS EMPLOYING THE FEEDFORWARD LINEARIZED MQW-EA EXTERNAL MODULATOR" see the whole document	1-7,10
A	IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 3, no. 9, September 1991, NEW YORK US, pages 844-846, XP000225799 K. SUTO ET AL.: "INTERMODULATION DISTORTION IN 48 TV CHANNEL FM-FDM OPTICAL TRANSMISSION" see the whole document	1-7,10
A	EP 0 658 016 A (ALCATEL SEL AKTIENGESELLSCHAFT) 14 June 1995 see abstract see column 1, line 3 - column 2, line 22 see column 4, line 1 - line 58	1,6,7,10
A	WO 92 13291 A (MASSACHUSETTS INSTITUTE OF TECHNOLOGY) 6 August 1992 see abstract see page 1, line 3 - page 5, line 24	1,6,7,10
A	IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 6, no. 9, September 1994, NEW YORK US, pages 1150-1152, XP000468088 J. WU ET AL.: "A FIBER DISTRIBUTION SYSTEM FOR MICROCELLULAR RADIO" see the whole document	1,9,10

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 96/02855

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
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		JP-A-	3179824	05-08-91
		US-A-	5161044	03-11-92
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		CA-A-	2058580	01-07-92
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