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(54) **Title**: OPTICAL SIGNAL PROCESSING

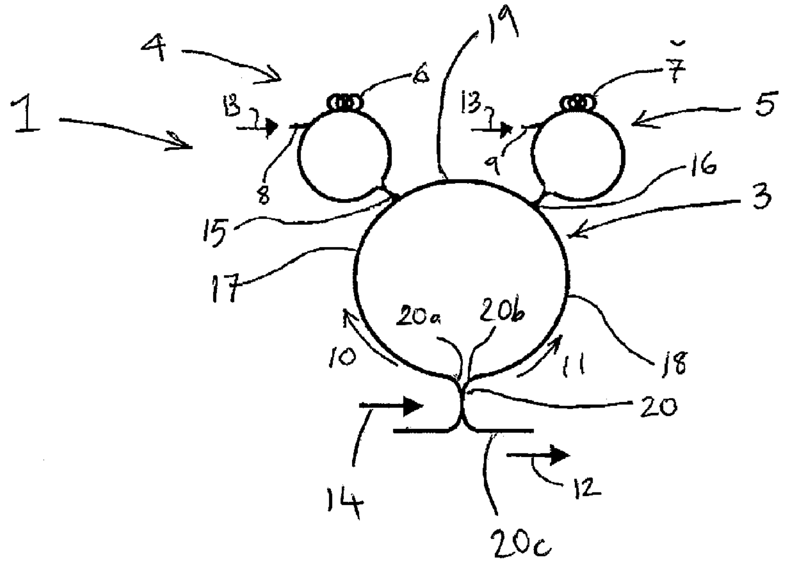

FIGURE 1

(57) Abstract: Optical signal processor (1) comprising an optical waveguide loop (3), and first and second phase modulator loops (6, 7), each of the first and second phase modulator loops is in optical communication with the optical waveguide loop, and the first and second phase modulator loops each comprises a respective control signal input port (8, 9) to control phase modulation applied by the phase modulation loops, and the optical waveguide loop comprising two input ports (20a, 20b) to direct input signals (10, 11) in opposite senses in the optical waveguide loop and further comprising an output port (20c) to output resulting signals. The first and second phase modulator loops may comprise nonlinear optical loop mirrors. The processor may be an optical logic gate device.

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OPTICAL SIGNAL PROCESSING

TECHNICAL FIELD

The present invention relates to optical signal processing.

BACKGROUND

The need for all-optical signal processing techniques arises from electronics limits such as computing and transmission speed, electromagnetic interference, power consumption, and insufficient bandwidth for ultra-fast applications. Known optical processors show the possibility to fulfil all optical signal processing by means of diverse optical devices such as Semiconductor Optical Amplifiers (SOAs), Semiconductor Saturable Absorber Mirrors (SESAMs) and single or cascaded Nonlinear Optical Loop Mirrors (NOLMs).

Integrable solutions, like those mentioned above, are interesting for their applications but currently are not able to meet acceptable performance in terms of fast dynamics and reconfigurability.

SUMMARY

According to the invention there is provided an optical signal processor comprising an optical waveguide loop, and first and second phase modulator loops. Each of the first and second phase modulator loops is in optical communication with the optical waveguide loop, and the first and second phase modulator loops each comprises a respective control signal input port to control phase modulation applied by the phase modulation loops. The optical waveguide loop comprises two input ports to direct input signals in opposite senses in the optical waveguide loop and further comprises an output port to output resulting signals.

The invention also provides a method of processing optical signals comprising causing two input signals to counter-propagate in an optical waveguide loop, and pass through first and second phase modulator loops. The first and second phase modulator loops are in optical communication with the optical waveguide loop The method further comprises feeding a control signal into a control port of each of the first and second phase modulator loops so as to control phase modulation applied to the input signals by each of the phase modulators, and combining the resulting signal components to produce an output signal.

DESCRIPTION OF THE DRAWINGS

Various embodiments of the invention will now be described, by way of example only, with reference to the following drawings in which:

Figure 1 is an optical signal processor,

Figure 2 is a block diagram of an optical signal processor,

Figure 3 is an optical signal processor,

Figures 4 to 7 are outputs represented graphically of an optical signal processor, and

Figures 8 and 9 are further optical signal processors.

DETAILED DESCRIPTION

With reference to Figure 1 there is shown an optical signal processor 1 comprising an optical waveguide loop 3 and first and second nonlinear phase modulator loops 4 and 5 which are coupled to the optical waveguide loop 3. Each phase modulator loop comprises a Highly Nonlinear Fibre (HNLF) portion 6 and 7, and a respective input port 8 and 9.

Each phase modulator loop 4 and 5 comprises a Cross Phase Modulation (XPM) based Polarisation Maintaining (PM) Nonlinear Optical Loop Mirror (NOLM) (indicated with $N^{(k)}$, $k = 1, 2$. in Fig. 2 right) are connected by three fibre spans 17, 18 and 19 and a respective coupler 15 and 16 ($C(\rho)$ as in (2)) is provided for each phase modulator. Generally if D is a fibre span then $D^{(i)} = e^{j\beta L_F^{(i)}}$, $i = 1,2,3.$ where $L_F^{(i)}$ is the i-th fibre length. An input signal 14 is fed into the processor 1 at the splitter 20 which has two input ports 20a and 20b to produce two input signals into the respective fibre spans 17 and 18 to produce two input signal components 10 and 11.

In order to better understand the manner of operation of the processor 1, we consider one of each of the phase modulators 4 and 5, which as stated above comprises a PM-NOLM device. We refer to Figure 3 which is shown as a PM-NOLM 100. The device 100 comprises a Highly Non-Linear Fibre (HNLF) of length L_{HNLF} [m] and non-linear coefficient γ [$W^{-1}Km^{-1}$], and two couplers 101 and 102, the former used to introduce the power of a pump signal at a wavelength λ_p (dashed arrows) into the loop, the latter to complete the NOLM structure as well as to allow the insertion of input fields and drop of output ones. The couplers have splitting ratios ρ_p and ρ respectively.

In the PM-NOLM 100 all the components are polarization maintaining. Although this aspect can limit the flexibility of the scheme (non-PM fibres require the use of a polarization controller in the loop that adds a degree of freedom in the optimization process), use of a PM configuration in order to simplifies the model, considering all fields as polarized along the fibre birefringence slow axis. In such a way, it is easier to predict the behavior of the system and adjust the input parameters to obtain the desired response.

Each NOLM can be considered as a single basic quadripole (as shown schematically in Figure 3) defined through its 2x2 matrix N.

The block accepts an input vector $\overline{E_{in}}$ (solid arrows) and returns an output vector $\overline{E_{out}}$ (dotted arrows) that can be found as:

$$\overline{E_{out}} = \begin{bmatrix} E_{out}^{1} \\ E_{out}^{2} \end{bmatrix} = N\overline{E_{in}} = N\begin{bmatrix} E_{in}^{1} \\ E_{in}^{2} \end{bmatrix};$$

$$where : N = \sqrt{\rho_p}\, e^{j\varphi_L} \begin{bmatrix} \sqrt{\rho(1-\rho)}\left(1+e^{j\varphi_{NL}}\right)e^{j\frac{\pi}{2}} & \rho-(1-\rho)\,e^{j\varphi_{NL}} \\ \rho\, e^{j\varphi_{NL}} -(1-\rho) & \sqrt{\rho(1-\rho)}\left(1+e^{j\varphi_{NL}}\right)e^{j\frac{\pi}{2}} \end{bmatrix} \quad (1)$$

.

Equation (1) states that the PM-NOLM 100 processes the input fields introducing two different phase shifts: a linear one, φ_L, which is referable to the delay caused by the loop length L_{loop}, $\varphi_L = \beta L_{loop}$ (β is the propagation constant of the electrical field in fibre) and a nonlinear one, φ_{NL}, that is due to the XPM effect induced by the pump power on the input field in the highly non linear fiber $\varphi_{NL} = 2\gamma(1-\rho_p)P_p L_{HNLF}$, where P_p is the instantaneous pump power and the coupler loss has been taken into account. The model assumes the input signals to be continuous waves at a certain wavelength $\lambda_{in} \neq \lambda_p$.

We can describe these elements with matrices as reported in equations (2) where *C* models the behavior of a coupler with splitting ratio *ρ* and *D* represents the phase shift induced by a fibre span of length L_F.

$$C = \begin{bmatrix} \sqrt{\rho} & \sqrt{1-\rho}\, e^{j\frac{\pi}{2}} \\ \sqrt{1-\rho}\, e^{j\frac{\pi}{2}} & \sqrt{\rho} \end{bmatrix}; \quad D = \left[e^{j\theta}\right], \theta = \beta\, L_F. \quad (2)$$

Returning now to the processor 1, our interest is focused on Reflectivity (*R*) and Transmittivity (*T*) as functions of the nonlinear phase shifts ($\varphi_{NL}^{(1)}, \varphi_{NL}^{(2)}$) which can be easily ascribed to the pump powers ($P_p^{(1)}, P_p^{(2)}$) by linear conversion; the linear phase shifts introduced in the structure depend on the particular fibre span or loop lengths of 17, 18 and 19 and are considered as parameters in the following equations that define the Transmittivity (*T*) and the Reflectivity (*R*):

$$T(\varphi_{NL}^{(1)},\varphi_{NL}^{(2)};\varphi_{L}^{(1)},\varphi_{L}^{(2)},\theta^{1},\theta^{2},\theta^{3})=\frac{P_{out}^{T}}{P_{in}}=\frac{\left|E_{out}^{T}\right|^{2}}{\left|E_{in}\right|^{2}};$$
$$R(\varphi_{NL}^{(1)},\varphi_{NL}^{(2)};\varphi_{L}^{(1)},\varphi_{L}^{(2)},\theta^{1},\theta^{2},\theta^{3})=\frac{P_{out}^{R}}{P_{in}}=\frac{\left|E_{out}^{R}\right|^{2}}{\left|E_{in}\right|^{2}}. \quad (3)$$

By substituting the expressions of E_{out}^{R} and E_{out}^{T} obtained from the block diagram in Fig. 2, it is possible to demonstrate that θ^1 and θ^2 appear in the Transmittivity and Reflectivity functions only in the term $\Delta\theta = \theta^1-\theta^2$ and thus we can say that *T* and *R* depend on the relative path lengths of fibre spans 17 and 18 and not on the specific lengths of each of the fibre spans.

In use of the processor 1, the input signal components 10 and 11 enter the processor 1 by input ports 20a and 20b and propagate in opposite senses in the loop 3. The signal component 10 enters the phase modulator loop 4 and the signal component 11 enters the phase modulator loop 5. After having passed through each HNLF, and having been phase modulated thereby, on exiting the respective modulator loop at couplers 15 and 16 they propagate through the span 19 and the n pass around the other phase modulator loop. The resulting signal components are then combined at the output 20c of the coupler 20. The relative phase between the signals being combined at the output 20c will determine the type of interference which occurs as a result of the signals

By appropriate linear phase shifts tuning, different Transmittivity and Reflectivity functions can be obtained. The splitting ratios of the couplers' 15. 16 and 20 are equal to 0.5. We show here a set of results obtained for different parameter values. All results suppose the input field E_{in} to be a continuous wave at λ_{in}= 1550 nm.

By introducing a linear dependence between the nonlinear phase shifts (and consequently between the pump powers) caused by the phase modulators 4 and 5 different Reflectivity and Transmittivity curves can be extracted from the bi-dimensional plots as in Figure 4. In Figure 4, an *R*-curve with a steep soft limiting function serves as an efficient in-line data regenerator.

Figure 5 shows a *T*-curve that can be exploited as logical port: the input signals of the port $S_1(t)$ and $S_2(t)$ are combined to form the control signals 13 to the phase modulator loops 4 and 5 and so the phase shifts are exactly the same for each XPM-based NOLM block. Figure 5 also shows the truth table of the corresponding NOR logic gate. In Figures 4 and 5, and referring back to the equations set out above, $\theta^1=0°$, $\theta^2=0°$, $\theta^3=0°$, $\Delta\varphi_{NL}=0°$.

Steeper curves can be obtained by tuning the set of parameters θ^1, θ^2, θ^3, $\Delta\varphi_{NL}$. As shown in Figure 7. Figure 6 shows a different use of the bi-dimensional plot. Here the nonlinear phase shifts that are directly dependent on the pump powers are utilized as input signal for a NOR logical gate. This way the pump signals are directly proportional to the input signal of the logic gate. In Figures 6 and 7, $\theta^1=0°$, $\theta^2=0°$, $\theta^3=130°$, $\Delta\varphi_{NL}=190°$

In addition to the processor 1 in Figure 1, other configurations are possible, depending on the functionality required. For example Figures 8 and 9 show two further optical processors 200 and 300 respectively, which are embodiments of the invention. In Figure 8, a NOLM structure 201 is connected to two spaced apart NOLM structures 202 and 203, with NOLM structure 204 directly connected to NOLM 203 only. In Figure 9 a principle NOLM structure 301-302 is connected to single NOLM structures 303 and 304.

Advantageously, the processor 1 is readily reconfigurable, for example to perform a different logic operation by simply adjusting the difference in path length between spans 17 and 18. This can be achieved by inserting tunable optical delay lines in the path to be tuned. The processor 1 allows implementation of an arbitrary, reconfigurable non-linear optical transfer function by combining elementary XPM-based PM NOLM blocks without changing the system architecture but by simply tuning a set of optical input parameters. Moreover, the processor provides fast dynamics performance.

All curves shown in Figures 5 to 7 are compared with the corresponding single NOLM *T* or *R* function (dashed curves) that have sinusoidal shapes.

CLAIMS

1. Optical signal processor (1) comprising an optical waveguide loop (3), and first and second phase modulator loops (6, 7), each of the first and second phase modulator loops is in optical communication with the optical waveguide loop, and the first and second phase modulator loops each comprises a respective control signal input port (8, 9) to control phase modulation applied by the phase modulation loops, and the optical waveguide loop comprising two input ports (20a, 20b) to direct input signals (10, 11) in opposite senses in the optical waveguide loop and further comprising an output port (20c) to output resulting signals.

2. Optical signal processor as claimed in any preceding claim in which the phase modulator loops (6, 7) are in communication with the optical waveguide loop (3) at different respective positions (15, 16) on said optical waveguide loop.

3. Optical signal processor as claimed in claim 1 or claim 2 in which the path length of a span of fibre (17) of the optical waveguide loop (3) which extends from the output port (20) of the optical waveguide loop to the first phase modulator loop (6) is unequal to the path length of another span of fibre (18) of the optical waveguide loop which extends from the output port to the second phase modulator (7).

4. Optical signal processor as claimed in claim 3 in which at least one of the path lengths is arranged to be adjustable relative to the other path length.

5. Optical signal processor as claimed in any preceding claim in which at least one of first and second phase modulator loops (6, 7) comprising a nonlinear optical mirror.

6. Optical signal processor as claimed in any preceding claim in which at least one of the phase modulation loops comprises a portion of a material whose refractive index changes nonlinearly with the intensity of a control signal.

7. Optical signal processor as claimed in any preceding claim which is an optical logic gate device.

8. A method of processing optical signals comprising causing two input signals (10, 11) to counter-propagate in an optical waveguide loop (3), and pass through first and second phase modulator loops (4, 5), the first and second phase modulator loops being in optical communication with the optical waveguide loop, the method further comprising feeding a control signal (13) into a control port (8, 9) of each of the first and second phase modulator loops so as to control phase modulation applied to the input signals by each of the phase modulators, and combining the resulting signal components to produce an output signal (12).

9. A method as claimed in claim 8 which is a method of performing a logic operation on at least two binary signals (13).

10. A method as claimed in claim 9 in which both of the at least two binary signals are fed into the control port of each of the first and second phase modulator loops (4, 5).

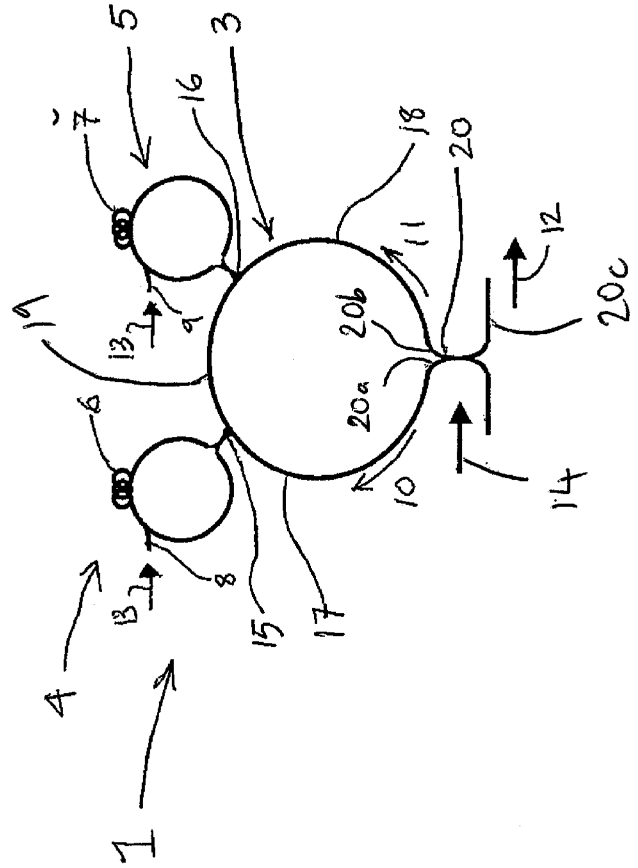


FIGURE 1

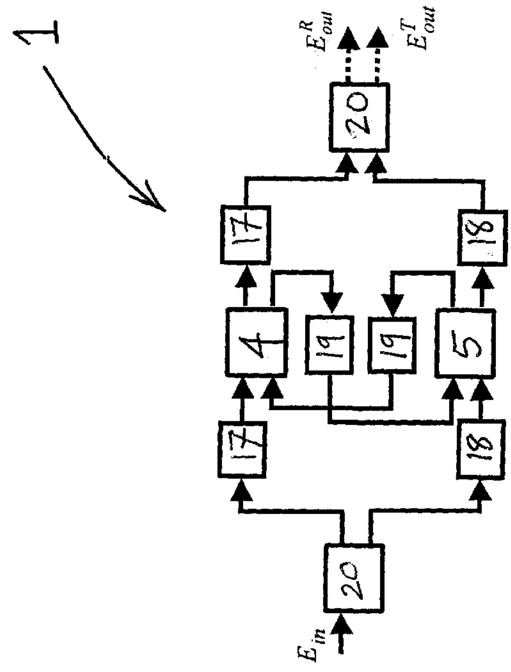


FIGURE 2

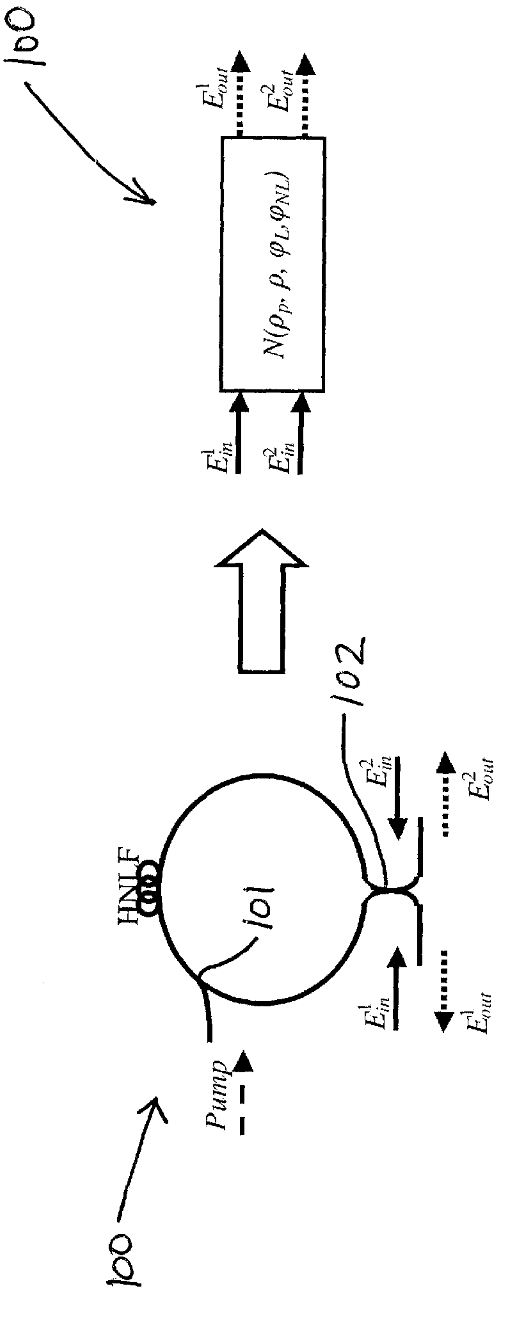

100
E_{out}^1
E_{out}^2
$N(\rho_P, \rho, \varphi_L, \varphi_{NL})$
E_{in}^1
E_{in}^2
102
HNLF
101
E_{in}^2
E_{out}^2
E_{in}^1
E_{out}^1
Pump
100

FIGURE 3

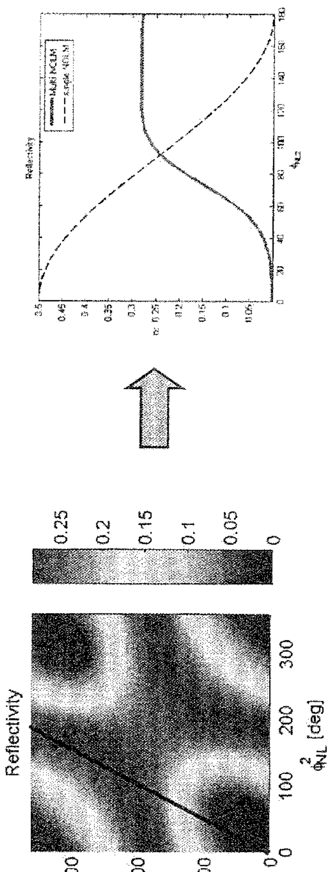
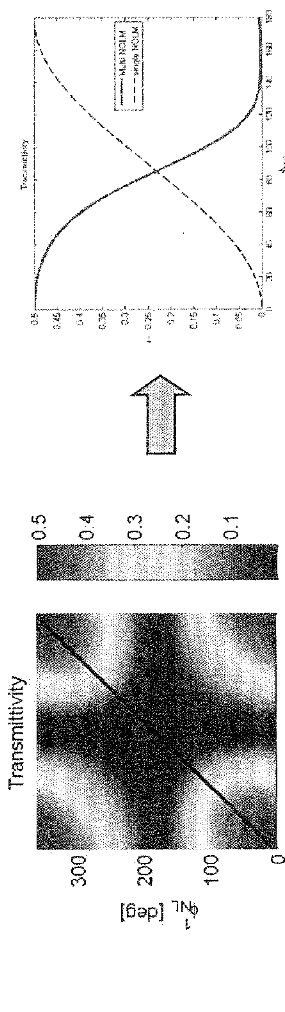

Reflectivity
ϕ^1_{NL} [deg]
ϕ^2_{NL} [deg]
0 100 200 300
0.25 0.2 0.15 0.1 0.05 0
Reflectivity

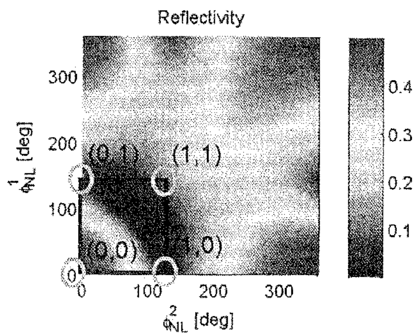
FIGURE 4



$$\varphi^2_{NL} = S_1(t) + S_2(t)$$

$S_1(t)$	$S_2(t)$	Out (NOR)
0	0	1
0	1	0
1	0	0
1	1	0

FIGURE 5



φ^2_{NL}	φ^1_{NL}	Out (NOR)
0	0	1
0	1	0
1	0	0
1	1	0

FIGURE 6

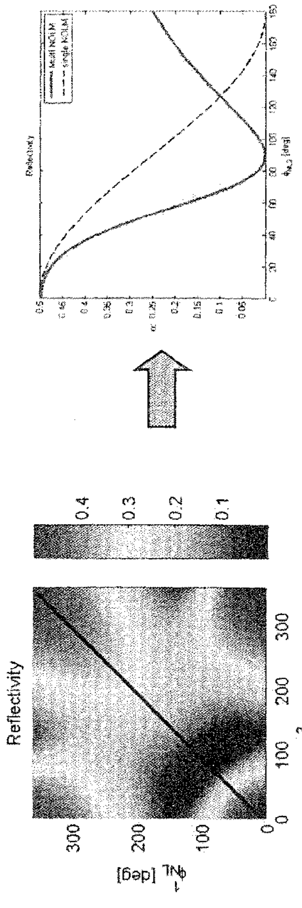


FIGURE 7

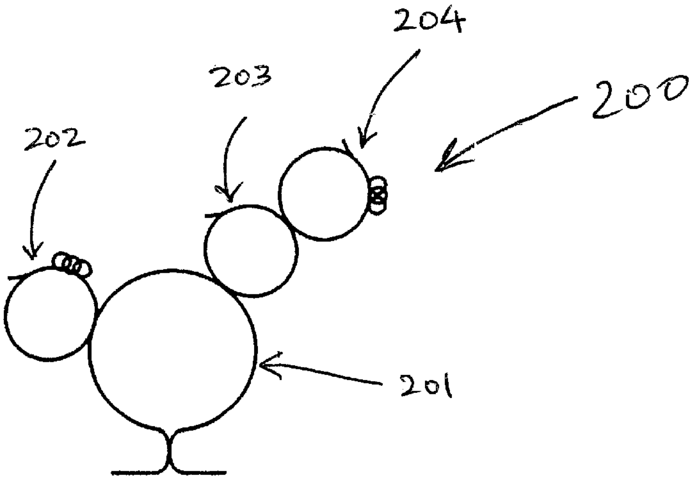


FIGURE 8

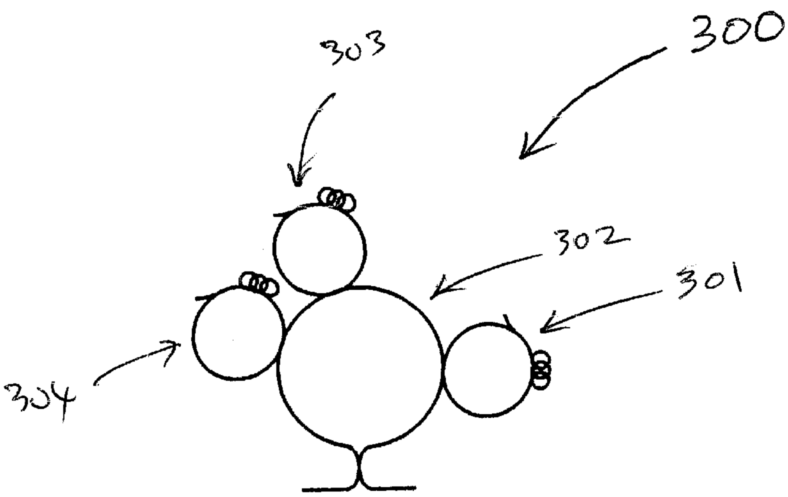


FIGURE 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2008/052537

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02F1/35 G02F3/00

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)
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)

EPO-Internal, WPI Data, INSPEC, COMPENDEX, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A		4-10
A	US 5 493 433 A (PRUCNAL PAUL R [US] ET AL) 20 February 1996 (1996-02-20) column 2, line 64 - column 4, line 16; figure 1	1,8
A	EP 0 456 422 A (AMERICAN TELEPHONE & TELEGRAPH [US] AT & T CORP [US]) 13 November 1991 (1991-11-13) column 5, line 3 - line 49; figure 1	1,8
	-/--	

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

[X] See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 July 2008	05/08/2008

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Lord, Richard

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2008/052537

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	MASAHIKO JINNO ET AL: "NONLINEAR SAGNAC INTERFEROMETER SWITCH AND ITS APPLICATIONS" IEEE JOURNAL OF QUANTUM ELECTRONICS, IEEE SERVICE CENTER, PISCATAWAY, NJ, vol. 28, no. 4, 1 April 1992 (1992-04-01), pages 875-882, XP000272712 ISSN: 0018-9197 the whole document -----	1,8

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2008/052537

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