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(71) Applicant: PHILIPS ELECTRONICS N.V. [NL/NL]; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL).

(71) Applicant (for SE only): PHILIPS NORDEN AB [SE/SE]; Kottbygatan 7, Kista, S-164 85 Stockholm (SE).

(72) Inventor: DEPOVERE, Geert, Florimond, Gerard; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL).

(74) Agent: DEGUELLE, Wilhelmus, Hendrikus, Gerardus; Internationaal Octrooibureau B.V., P.O. Box 220, NL-5600 AE Eindhoven (NL).

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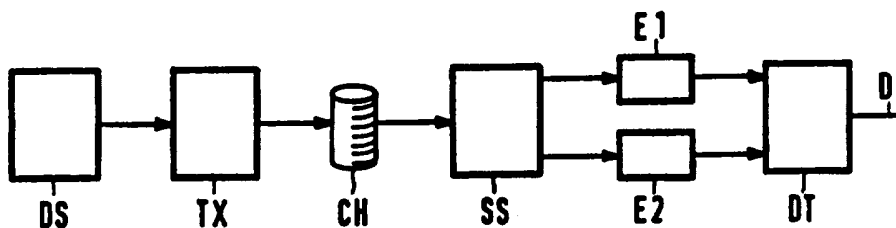
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(54) Title: A COHERENT OPTICAL COMMUNICATION SYSTEM AND A COHERENT OPTICAL RECEIVER

(57) Abstract

A coherent optical communication system comprises an information source (DS) and a transmitter (Tx) for modulating information onto a carrier for transmission over a channel (CH). A receiver for signals transmitted over the channel operates on a phase diversity principle. In order that effective equalisation



of the received signals may be provided the signal is down-converted to substantially baseband quadrature and then the upper sideband and the lower sideband are separated (SS) and equalised (E1, E2) independently. The system solves the problem of applying equalisation to a down-converted signal folded around zero frequency by separating the sidebands of the signal first. The amount of high frequency electronics required at an optical receiver in a coherent optical communications system may thus be reduced. The invention further relates to the optical receiver for use in such a coherent optical communication system.

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A COHERENT OPTICAL COMMUNICATION SYSTEME AND A
COHERENT OPTICAL RECEIVER

The present invention relates to an optical communication system having particular, but not exclusive, application to coherent communication of digital information over an optical channel. The invention also relates to an optical receiver for use in such a communication system.

5 Communication of information over optical fibres is becoming ever more widespread as a result of cost and size advantages over other forms of communication. Of particular interest are coherent optical communication systems which allow the vast bandwidth of optical fibres to provide many channels through wavelength division multiplexing. One source of problems with this type of communication is that of dispersion
10 in the fibre meaning that different frequency components of the optical signal propagate at different speeds and this results in a distorted signal at the receiver. Equalisation of the received signal is necessary except for short distance, low bandwidth communication. In heterodyne receivers equalisation is readily applied at the Intermediate Frequency (IF) section of the receiver but the IF section must operate at a comparatively high frequency which
15 makes the circuitry difficult, if not impossible to integrate. Zero-IF receivers, which are readily integrated, may be used but the spectrum of the IF signal is folded about zero frequency with the consequence that complete equalisation of the signal is not possible.

 Japanese patent application publication number 2-159134 describes an optical receiver for solving this problem in which quadrature down-converted optical signals
20 are transformed to the electrical domain and up-converted to a second intermediate frequency for equalisation to be applied. This arrangement thus provides the equalisation for dispersion in an analogous way to that of a heterodyne receiver. However, much of the advantage derived from using a zero-IF receiver is lost because of the further frequency conversion stage required and the high frequency signals with which the subsequent electronic circuitry
25 must deal. In a digital communication system operating at 10 Gbit/second these frequencies will typically be as high as 30 GHz so the problems associated with high frequency circuitry will still apply.

 It is an object of the present invention to provide an optical communication system which overcomes this drawback.

According to a first aspect of the present invention there is provided a coherent optical communication system comprising a source of an information signal, a transmitter for modulating the information signal onto a lightwave carrier to provide a modulated carrier signal, a channel for conveying the modulated carrier signal and a receiver
5 comprising means for down converting the modulated carrier signal to a substantially baseband signal, characterised by means for separating at least one sideband of the baseband signal and means for equalising the at least one sideband of the baseband signal.

The present invention is thus based upon the realisation that the equalisation may be applied to the received signal in an optical communication system using
10 a zero-IF receiver if the two sidebands of the received signal are separated before the equalisation is applied. While the equalisation and subsequent demodulation may be applied to only one sideband (since the two carry the same information) there is a 3dB penalty paid for so doing and generally both sidebands will be equalised and then demodulated.

It is a further object of the present invention to provide an optical zero-IF
15 receiver for use in a communication system in accordance with the first aspect of the invention.

According to a further aspect of the present invention there is provided a coherent optical receiver comprising means for down-converting a received optical signal substantially to baseband and means for equalising the down-converted signal, characterised
20 by means for separating at least one of the upper sideband and the lower sideband of the down-converted signal before equalisation.

Various equalisation techniques employed to compensate for the dispersion in optical fibres are known. It must of course be borne in mind when designing the equaliser or equalisers that the dispersion characteristics of the optical fibre are being compensated
25 over a smaller range of frequencies corresponding to one sideband of the signal. In addition, the type of equalisation will differ because in a baseband receiver the lower sideband of the received signal is folded around DC meaning that the compensation to be applied will have the opposite characteristic to that for the upper sideband.

The separation of the sidebands of the received signal may be carried out
30 in the optical domain or in the electrical domain. Separation in the optical domain has the advantage of fewer electrical components while separation in the electrical domain can provide a higher signal bandwidth capability.

The present invention will now be explained, by way of non-limiting examples, with reference to the accompanying drawings, in which;

Figure 1 is a sketch of two curves with respect to frequency to assist in an understanding of the present invention,

Figure 2 is a block schematic diagram of a communication system in accordance with the present invention,

5 Figure 3 is a block schematic diagram of an optical receiver in accordance with the invention in which the sidebands of a down-converted signal are separated in the electrical domain,

Figure 4 is a sketch of frequency spectra to aid understanding of the invention,

10 Figure 5 is a block schematic diagram of a part of a receiver in accordance with the invention in which the sidebands of a down-converted signal are separated in the optical domain,

Figure 6 shows a series of polarisation diagrams relating to the operation of the arrangement of Figure 5, and

15 Figure 7 is a sketch of frequency spectra relating to the operation of the arrangement of Figure 5.

Figure 1 shows a sketch of a frequency spectrum of an input signal IS centred on a carrier frequency f_c and a channel response CR, for example that of an optical fibre. The channel response shown will delay the two sidebands of the signal to a somewhat
20 different extent. Using a phase diversity receiver the phase distorted input signal is down-converted to zero frequency so the lower sideband of the input signal will be folded around DC. It has proved impossible to fully compensate such a down-converted signal for the effect of the channel dispersion.

Figure 2 shows a block schematic diagram of a communication system in
25 accordance with the present invention. An information or data source DS provides a digital signal (although analogue signals are possible) to an optical transmitter Tx which modulates the information onto an optical carrier for transmission over an optical fibre channel CH. The transmitter Tx may be one of a number of transmitters which transmit signals over the optical channel CH which signals are separated by wavelength division multiplexing. The
30 optical channel may comprise repeaters as necessary. The other end of the channel CH is coupled to a down conversion and sideband separation means SS which will be described in greater detail with reference to the following drawings. A first sideband of the received signal is coupled to a first equaliser E1 and the remaining sideband of the signal is coupled to a second equaliser E2. The two equalisers apply equalisation for the frequency dependent

delay caused by the channel CH and their equalised outputs are coupled to a demodulator/detector DT to derive an output signal D.

The receiver shown in Figure 3 comprises an optical fibre input 10 on which the received signal is supplied which fibre is coupled to an input of a polarisation controller 12. The polarisation controller may be, for example, a lithium niobate (LiNbO_3) crystal, which alters the polarisation of a signal applied to it in response to an applied voltage, controlled by a feedback loop sensitive to the output of the crystal. The polarisation controller is arranged to provide a signal which is circularly polarised and this signal is applied to a first input of a 3dB coupler 18. A second input of the coupler 18 is provided by an output 16 of a local oscillator laser 14 arranged to provide a linearly polarised output of 45° . A first output of the coupler 18 is connected to an input of a polarisation splitting coupler 20, and a second output of the coupler 18 (which is 180° out of phase with the first output) is connected to an input of a polarisation splitting coupler 22. The coupler 20 has a first output having a first polarisation coupled to a photodiode 24 and a second output having a second polarisation coupled to a photodiode 30. The coupler 22 has a first output having a first polarisation coupled to a photodiode 26 and a second output having a second polarisation coupled to a photodiode 32. The output from the diode 26 is subtracted from the output of the diode 24 and the difference connected to an input of an amplifier 28. Since the optical signals at the output of the coupler 18 are 180° out of phase this provides an increased input to the amplifier. The amplifier has an output which is connected to a first input to a 3dB, 90° electrical hybrid 36. The output from the diode 32 is subtracted from the output of the diode 30 and the difference connected to an input of an amplifier 34, which again provides an increased input to the amplifier. An output of the amplifier is connected to a second input of the electrical hybrid 36. The output of the hybrid 36 comprises two separate baseband signals U1, U2 which each contain one sideband of the received signal. These sideband signals are compensated for phase distortion separately in equalisers 38 and 40 whose operation is described below with reference to Figure 4. The outputs of the equalisers 38, 40 are connected to first inputs of mixers 42, 44 and to inputs of delay elements 46, 48 respectively. The outputs of the delay elements 46, 48 are connected to second inputs of their respective mixers 42, 44 and the outputs of the mixers are combined by a subtracter 50 to provide the demodulated output D from the receiver.

In operation, the output of the local oscillator laser has an output signal which has a nominal frequency equal to the centre frequency of the signal to be received. A feedback loop (not shown) will typically be used to maintain the local oscillator frequency.

The laser output has a linear polarisation of 45 degrees which is mixed with a circularly polarised version of the received signal. The first respective outputs of the two polarisation splitting couplers 20, 22 are detected by diodes 24, 26 to provide an in-phase channel and the second respective outputs of the couplers 20, 22 are detected by diodes 30, 32 to provide a quadrature channel. The hybrid operates to add the in-phase channel signal to a 90° delayed version of the quadrature channel and vice versa to provide a first sideband signal U1 and a second sideband signal U2 on separate output lines from the hybrid. Both of the sidebands are equalised in this example but, as discussed above, it may be desired that only one is equalised and demodulated. In this example the signal received is an FSK digital signal and a demodulator appropriate to this type of modulation has been shown. Alternative demodulation arrangements should be substituted according to the nature of the received signals, be they amplitude, phase or frequency modulated.

The operation of the electrical hybrid may be better understood by considering the mathematics of the sideband separation. As is known, a zero-IF receiver mixes the incoming signal to a pair of baseband signals in phase quadrature thus:

$$\begin{aligned} I(t) &= \cos [m(t)\omega_m t], & \text{the "in-phase" channel, and} \\ Q(t) &= \sin [m(t)\omega_m t], & \text{the "quadrature" channel.} \end{aligned}$$

Where ω_m is the frequency deviation and $m(t)$ is +1 for a "one" bit and -1 for a "zero" bit. $I(t)$ and $Q(t)$ are the effective inputs to the 3dB, 90° electrical hybrid 36 (Figure 3) and the outputs of the hybrid 36 are:

$$\begin{aligned} U_1(t) &= \sqrt{2} \cos [\omega_m t] & \text{and} & & U_2(t) &= 0 & \text{when } m(t) = +1 \\ U_1(t) &= 0 & \text{and} & & U_2(t) &= -\sqrt{2} \sin [\omega_m t] & \text{when } m(t) = -1 \end{aligned}$$

and thus the two sidebands of the optical signal are separated. $U_1(t)$ and $U_2(t)$ can be represented more neatly as:

$$\begin{aligned} U_1(t) &= \sqrt{[m(t) + 1]} \cos (\omega_m t) \\ U_2(t) &= \sqrt{[m(t) - 1]} \cos (\omega_m t) \end{aligned}$$

Figure 4 shows a sketch of the delay to be equalised in the upper sideband US and the lower sideband LS after the received signal has been down-converted to zero frequency. The signal is folded around DC so the lower sideband has been inverted in frequency and consequently requires different equalisation from the upper sideband. As is known, a microstrip line can be used in a heterodyne system to equalise the dispersion characteristics of the signal and such a technique is still appropriate for the upper sideband equaliser of the present invention. To equalise the lower sideband, however, an equaliser with the opposite characteristic is required and for this purpose a microwave waveguide is

suitable. Such a waveguide is described in "Equalisation of Coherent Lightwave Systems Using Microwave Waveguides" by Jack Winters in the IEEE Journal of Lightwave Technology, May 1989 pages 813 to 815. The sign of the slope of such equalisers is the reverse of that for a microstrip line so this provides the correct sense of equalisation to the lower sideband of the received signal. Figure 4 shows the slopes of the equalisation provided by the microstrip line MS and the waveguide WG in broken lines. The equalisers 38, 40 of Figure 3 may thus be arranged to comprise a microstrip line or a waveguide to apply the appropriate delay equalisation characteristic to the separated upper and lower sidebands of the received signal.

Figure 5 shows a schematic diagram of a receiver arrangement in which the frequency down-conversion and the separation of the sidebands of a received signal is performed totally in the optical domain. The incoming signal on a fibre 10 is coupled to an input of a polarisation controller 70 arranged to provide a linearly polarised version of the input signal at 45° . A local oscillator laser 72 provides an output signal on line 74 which signal has a circular polarisation. These two signals are combined in a 3dB optical coupler 75 whose outputs are each coupled to a length of Polarisation Maintaining Fibre (PMF) 76, 78. These fibres, as their name suggests, maintain the polarisation of the light signals within them over long distances and a mechanism by which this behaviour can be maintained, modal birefringence, is described at page 100 onwards of "Optical Fibre Communications - Principles and Practice" by John Senior (Prentice Hall International). Briefly, the refractive indices of polarisation maintaining fibres differ between the two axes of polarisation as a result of deliberate stresses applied to the fibre during manufacture. The PMF 76, 78 have a property known as beat length as a consequence of slight differences in the phase velocities of the two orthogonally polarised modes of propagation within them and it typically has a value of a few centimetres. Over the beat length of a fibre the polarisation states of a signal being carried by it will vary from linearly polarised through circularly polarised to linearly polarised in the orthogonal direction and then back again through reverse circularly polarised to linear polarisation in the same sense as the signal originally. The beat length is dependent upon the frequency of the light signal and so the local oscillator signal, the lower sideband and the upper sideband of the input signal will all have different values of beat length. At various distances from the ends of the PMFs 76, 78 each sideband of the received signal will have a polarisation equal to that of the local oscillator signal which polarisation is mutually perpendicular to that of the other sideband. The lengths of the PMFs are chosen to equal these lengths as will be described below with reference to Figure 6. The outputs of the PMF

76, 78 represent the two sideband signals and are coupled to detectors, for example photodiodes 80, 82. The signals with coincident polarisations are mixed, converted to the electrical domain and the separate sidebands are then compensated for dispersion as previously described. To ensure correct operation, the 3dB coupler 75 can either itself be
5 made from PMF or it can be connected to the polarisation controller 70, the local oscillator 72 and the PMF 76, 78 by very short lengths of optical fibre. The arrangement of Figure 5 can, of course, be simplified to derive only one sideband of the down-converted signal for subsequent dispersion compensation and demodulation.

Figure 6 shows the variation of polarisation with distance for the three
10 frequency components propagating in the polarisation maintaining optical fibres 76, 78 of Figure 5. The top most line of symbols in Figure 6 is for the upper sideband of the received signal, the middle line is for the lower sideband of the received signal and the bottom line is for the local oscillator signal provided by the laser 72. The frequency dependency of the beat length of the signals in the polarisation maintaining fibre means that the beat length of the
15 upper sideband spectral component is half of that of the lower sideband component and the local oscillator component has a beat length in between the two. Since the polarisation of the incoming signal is arranged to be 45° linear and that of the local oscillator component is initially circular, the polarisations of the three frequency components vary with distance as shown. As can be seen the local oscillator signal has the same polarisation as the upper
20 sideband component and perpendicular polarisation to the lower sideband component at point b which is one beat length from the optical coupler at the upper sideband frequency. The local oscillator signal has the same polarisation as the lower sideband component and perpendicular polarisation to the upper sideband component at point d which is three beat lengths from the optical coupler at the upper sideband frequency. Hence the PMF 76 in
25 Figure 5 is equal to one beat length at the upper sideband frequency and the PMF 78 is equal to three times this length. Different combinations of fibre length and signal polarisation may be employed depending upon the particular frequencies of the signals. Alternative techniques to separate the sidebands of the received signal in the optical domain may also be used.

While reference has been made above to the upper sideband frequency and
30 the lower sideband frequency it should be appreciated that these are not distinct frequencies but instead a band of frequencies whose width depends upon the modulation applied to the carrier by the transmitter of the communication system. The technique for separating the sidebands that was described with reference to Figure 3, in other words the electrical separation technique, has good bandwidth performance but the optical separation technique of

Figure 5 is likely to lose some signal information close to DC due to the wavelength sensitive behaviour of PMF. This is illustrated by the dot-dash line in Figure 7 representing this filtering effect which, for example, is a cosine function. For the FSK signal represented diagrammatically by the dotted lines, this presents little or no problem. For signals such as 5 CPFSK, however, whose spectrum is represented by the full line, too much information will be lost and reliable demodulation of the signal will be impossible.

CLAIMS

1. A coherent optical communication system comprising a source of an information signal, a transmitter for modulating the information signal onto a lightwave carrier to provide a modulated carrier signal, a channel for conveying the modulated carrier signal and a receiver comprising means for down converting the modulated carrier signal to a substantially baseband signal, characterised by means for separating at least one sideband of the baseband signal and means for equalising the at least one sideband of the baseband signal.
2. A communication system as claimed in Claim 1, characterised by means for separating the remaining sideband of the baseband signal and means for equalising the separated remaining sideband of the baseband signal.
3. A communication system as claimed in Claim 1 or Claim 2, characterised in that the means for separating the at least one sideband of the baseband signal operates in the electrical domain.
4. A communication system as claimed in Claim 1 or Claim 2, characterised in that the means for separating the at least one sideband of the baseband signal operates in the optical domain.
5. A coherent optical receiver comprising means for down-converting a received signal substantially to baseband and means for equalising the down-converted signal, characterised by means for separating at least one of the upper sideband and the lower sideband of the down-converted signal before equalisation.
6. An optical receiver as claimed in Claim 5, characterised by equalisation means for equalising both the upper sideband and the lower sideband of the down-converted signal.
7. An optical receiver as claimed in Claim 5 or Claim 6, characterised by sideband separating means arranged to operate in the optical domain.
8. An optical receiver as claimed in Claim 5 or Claim 6, characterised by sideband separating means arranged to operate in the electrical domain.
9. An optical receiver as claimed in Claim 8, characterised by at least one polarisation splitting coupler to provide phase quadrature signals, an optical to electrical

converter for each electrical signal and a 90° electrical hybrid for providing separated sidebands.

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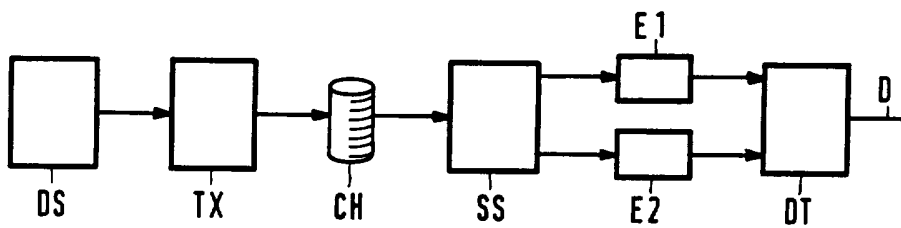
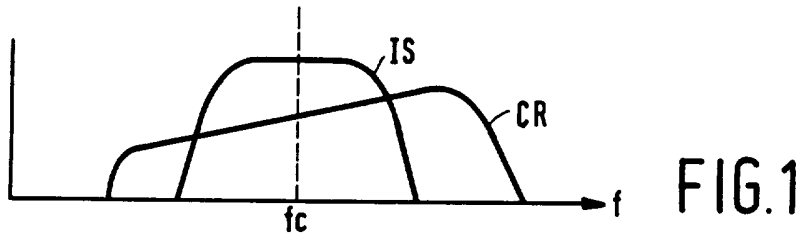


FIG. 2

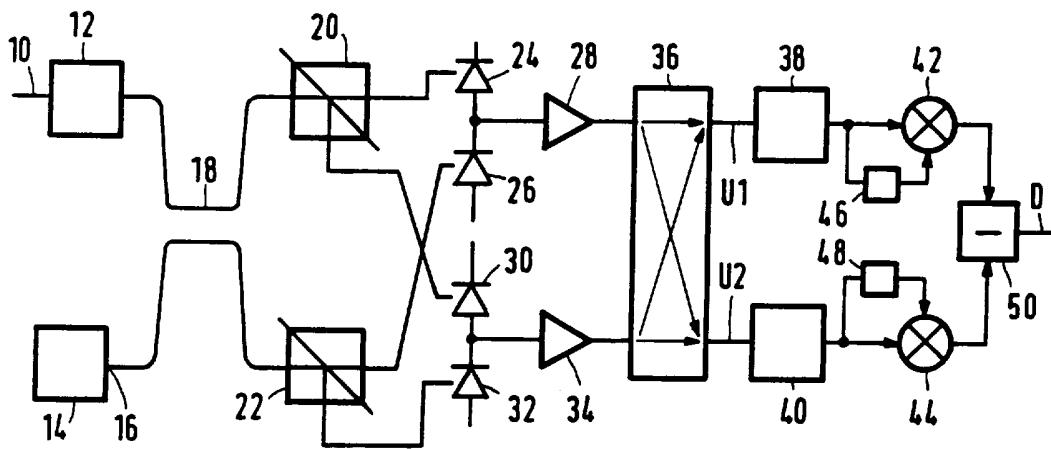


FIG. 3

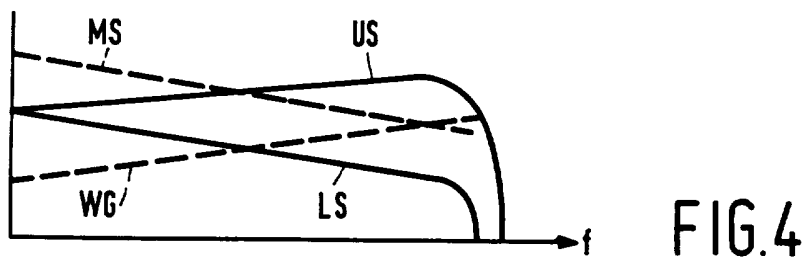


FIG. 4

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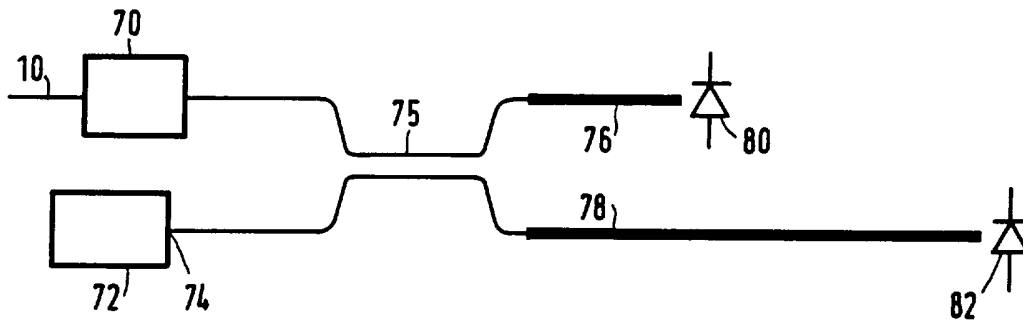


FIG.5

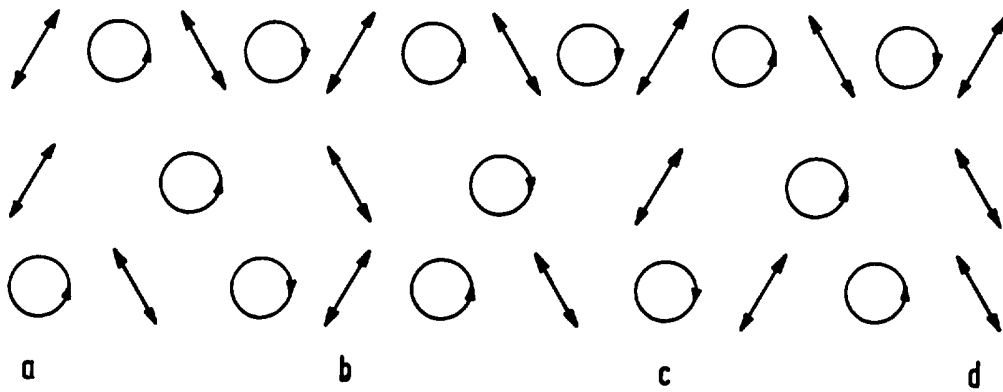


FIG.6

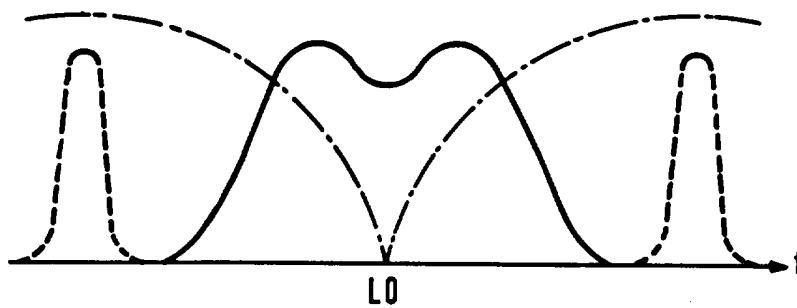


FIG.7