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The Applicant(s)/Nominated Person(s) has/have entitlement from the actual inventor(s) as follows:-

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The basic application(s) listed on the Declaration under Article 8 of the PCT is/are the first application(s) made in a Convention country in respect of the invention.

DATED this FIFTH day of DECEMBER 19 94

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APPARATUS AND METHOD FOR THE LINEARIZATION OF THE SIGNAL TRANSFER OF AN INTEGRATED OPTICAL PHASE MODULATOR COMPRISING MODULATORS COUPLED IN CASCADE

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(57) Claim

1. An integrated optical phase modulator for modulating a light signal, comprising:

a substrate;

light signal receiving means for receiving and dividing a light signal into first and second light input signals of substantially equal power level;

first optical phase modulator means for receiving said first and second light input signals, and modulating the light input signals by a first rf signal, thereby producing modulated first and second complementary secondary output signals;

a first optical coupler having a pair of input ports for receiving said first and second secondary output signals, and a pair of output ports;

second optical phase modulator means connected to said pair of output ports of said first optical coupler for receiving and then modulating said first and second secondary output signals by a second rf signal, thereby producing complementary third and fourth secondary output

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signals;

a second optical coupler having a pair of input ports for receiving said third and fourth secondary output signals and a pair of output ports;

first and second light waveguide means, each having an input port connected to first and second output ports, respectively, of said second optical coupler, each having an output port for providing complementary and linearized first and second modulated light output signals,

said light signal receiving means, first and second optical phase modulator means, first and second optical couplers, and first and second waveguide means, all being formed on said substrate, wherein:

means for compensating for deviations of coupling angle values of said first and second optical couplers, respectively, from predetermined values, said compensating means including

first and second impedance matching circuitry means connected between individual output terminals of said means for compensating and individual rf signal inputs of said first and second optical phase modulator means, respectively, for ensuring a flat and equal frequency response by said first and second optical phase modulator means to said first and second rf signals.

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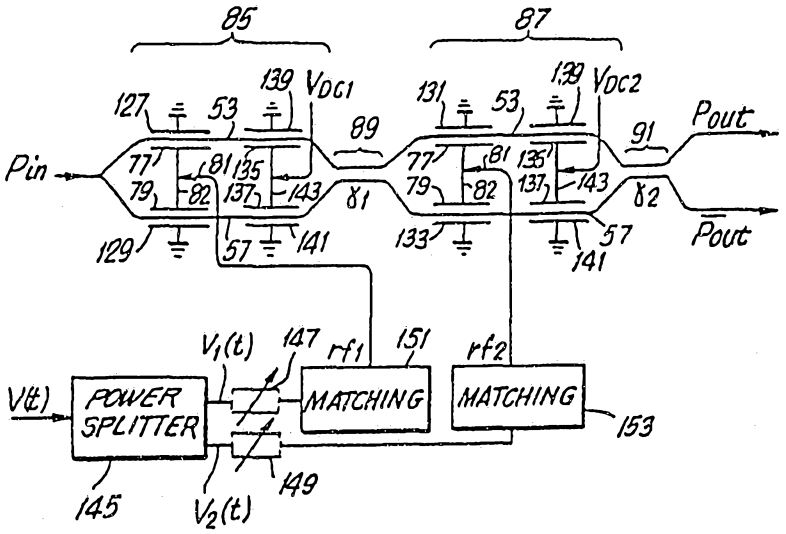
(54) Title: APPARATUS AND METHOD FOR THE LINEARIZATION OF THE SIGNAL TRANSFER OF AN INTEGRATED OPTICAL PHASE MODULATOR COMPRISING MODULATORS COUPLED IN CASCADE



(57) Abstract

An integrated cascaded optical phase modulator for providing linearized complementary modulated light output signals consists of the successive cascade of a first phase modulator stage (85), first fixed optical coupler (89), second phase modulator stage (87), and second fixed optical coupler (91). Rf modulating signals applied to each phase modulator stage are adjusted in amplitude, for compensating for errors in the coupling angles of the first and second optical couplers. The levels of DC bias voltages applied to each phase modulator stage are adjusted for compensating for asymmetric phase modulation. Impedance matching means (151, 152) connected between output terminals of rf modulating signals and phase modulators match the impedance therebetween.

Apparatus and method for the linearization of the signal transfer of an integrated optical phase modulator comprising modulators coupled in cascade.

Related Application

The present invention is related to Applicant's co-pending application Serial No 07/706,911, filed May 29, 1991, and entitled "APPARATUS AND METHOD FOR LINEARIZED CASCADE COUPLED INTEGRATED OPTICAL MODULATOR", which is incorporated herein by reference.

Field Of The Invention

This invention relates generally to modulators, and more particularly to a method and apparatus for providing linearized signal transfer in integrated electro-optical phase modulators.

Background Of The Invention

Integrated electro-optical modulators are finding increasing use in state-of-the-art analog optical-fiber communication systems. Such systems are being developed as an alternative to conventional electromagnetic transmission lines. Present optical-fiber communication systems may consist of a high power, low noise laser source in conjunction with a wide bandwidth external modulator, for example. Such external modulators may be used in conjunction with high power, low noise

lasers, to provide analog signal transfer in optical fiber cable T.V. networks. A common problem in such systems is that the dynamic range thereof is limited by intermodulation distortion, and by harmonic distortion due to modulator nonlinearities. Many attempts have been made in the art to improve the linearity of the modulators.

One method of improving the linearity of optical modulators is to provide electromagnetic predistortion of the input signal. A system for accomplishing this is reported in an article by R.P. Childs and D.A. O'Byrne, that appeared in OFC 90, entitled "Predistortion Linearization of Directly Modulated DFB Lasers and External Modulators for AM Video Transmission."

There are many examples of electro-optical modulators, demodulators, and modulating systems in the art. A number of such prior systems are briefly discussed below.

Johnson U.S. Patents 5,015,053 and 5,002,355 refer to linearization of an interferometric modulator by coupling to transverse electric (TE) and transverse magnetic (TM) modes. A carrier wave derived from a light source is polarized by a polarizer for adjusting the power of the carrier wave in the TE and TM polarization modes.

Hamilton et al. U.S. Patent 5,010,346 shows an electro-optical analog-to-digital converter. A laser light source is synchronized with a digital clock for producing pulses of light. The pulses of light are modulated by an optical modulator for varying the intensity of the pulses of light as a function of the amplitude of the analog modulating signal. The light pulses are

demultiplexed and passed through a detector for converting the light pulses to electrical signals. The electrical signals are then passed through an electrical analog-to-digital converter.

DuPuy et al U.S. Patent 4,997,245 shows optical switches that are polarization independent. The optical switches include a substrate of electro-optic material in which waveguides are formed in a manner permitting light waves to be switched therethrough independent of polarization phenomena.

Thylen U.S. Patent 4,993,798 refers to an optical communication system consisting of a semiconductor laser that includes an optical waveguide coupled at one end to first and second optical directional switches. The other ends of each one of the directional couplers each have an end of a waveguide terminated to a mirror, for forming a cavity including the laser diode. By either modulating current driving the diode, or by applying a modulating signal to the directional couplers, a light signal passing therethrough can be modulated.

Yoon et al U.S. Patent 4,936,645 shows a polarization-insensitive Mach-Zehnder modulator that includes a thin film waveguide on a substrate. The modulator consists of a lamination of different organic polymers upon which the thin film waveguide is deposited, and electrodes for applying voltages for producing electric fields to coact with the light passing through the waveguides.

Koai U.S. Patent 4,934,776 teaches the combination of cascaded individual waveguide directional coupler sections arranged to provide a high-density optical data array, for

forming an integrated optical intensity modulator. The cascaded coupled-waveguide modulators provide ultra-high extinction ratios.

Koai U.S. Patent 4,934,775 shows an optical space-division switching architecture consisting of high-extinction electro-optical data arrays of a plurality of cascaded coupled-waveguide optical intensity modulators. A plurality of passive splitter circuits are used to evenly divide an input optical signal into a plurality of interim optical signals. The optical signals are passed through the optical intensity modulators, respectively, which have waveguide coupler sections cascaded together on a crystal substrate to form a bar-type modulator structure, for providing a direct optical connection between the various sections of each modulator. Combiner circuits receive the output optical signals from the data arrays and combine them for providing a single output wave or signal.

Su U.S. Patent 4,932,736 teaches the monolithic integration of three integrated waveguide couplers to provide a 1X2 or 2X1 integrated optical switch with a high extinction ratio. In the switch a first waveguide coupler has its output directly coupled to the input ports of the other two waveguide couplers via an integrated waveguide. As a result, two cascaded integrated waveguide couplers are provided along each path from a single input port to two output ports, respectively.

Coleman U.S. Patent 4,882,775 shows a demodulator provided by a an interferometer and a signal processor. The demodulator is included in a coherence multiplexed, optical data

transmission system. The optical data transmission system includes an interferometric modulator at an input end. The output signals therefrom are modulated waveforms which are passed through an optical multiplexer, and coupled via single mode optical couplers and a fiber optic cable to demodulator stages. Each modulator and demodulator stage is provided by an unequal arm-length Mach-Zehnder interferometer. The multiplexers phase modulate the optical carriers from the modulators for multiplexing the same together. The path lengths between the modulators and demodulators included in the system are controlled for obtaining a desired output from the output demodulator stages 40.

Alferness U.S. Patent 4,390,236 shows an electro-optical demultiplexer consisting of a plurality of cascaded tunable, polarization independent optical wavelength filters. The various sections of the filters, as cascaded, provide an input polarization selective coupler that separates the transverse electrical (TE) and transverse magnetic (TM) orthogonally polarized wave components, respectively, of an arbitrarily polarized input signal. The separated TE and TM components then travel along two different wavepaths or waveguides. Each waveguide includes a wavelength selective mode converter. An output polarization selective coupler is provided for combining in one output waveguide signal components centered about the wavelength of the mode converters, and for combining in a second output waveguide the balance of the input signal.

Papuchon U.S. Patent 4,223,977 shows an integrated optical circuit for separating a plurality of optical waves of different wavelengths, thereby providing a demultiplexing function. A plurality of basic electro-optical cells are integrated on a single substrate for providing the optical demultiplexing circuit.

A paper entitled "Waveguide Modulators with Extended Linear Dynamic Range a Theoretical Prediction" (Z.Q. Lin and W.S.C. Chang, Photonics Technology Letters, Vol. 2, No. 12, Dec. '90) shows a modified-directional-coupler modulator with reduced nonlinear distortion. The coupler includes an input stage for receiving input signals for a voltage control directional coupler that couples the signals to a Mach-Zehnder interferometer. The output of the interferometer is coupled by a fixed directional coupler to an output waveguide providing two channels. The parameters are adjusted for minimizing third order intermodulation spurious signals.

A paper entitled "In Search of a Linear Electro-optic Amplitude Modulator" (Pao-Lo Liu, B.J. Li, and Y.S. Trisno, SPIE Conference, 1990) shows a linear electro-optic amplitude modulator. The modulator includes a Y-branch for dividing an optical input signal equally for inputting into the two arms, respectively, of a Mach-Zehnder interferometer. The interferometer functions as a phase shifter. The output of the interferometer is supplied to a directional coupler having a nominal coupling constant-length product of half a coupling length. The optical output signal is provided at each of two

output waveguides. A modulation signal of one polarity is applied to the interferometer phase shifter, and is applied in reverse polarity to the directional coupler using a multiplication factor. The parameters are adjusted for optimizing the linearity of the modulator by reducing the second and third order harmonics that cause nonlinearities to occur.

The present invention recognized that known integrated optics modulators require further improvement. One need recognized is to improve the linearity of integrated optical phase modulators.

In a paper entitled "Linearization of Electro-Optic Modulators By A Cascade Coupling Of Phase Modulating Electrodes" (Halvor Skeie and Richard V. Johnson, SPIE conference, Vol. 1583, Integrated Optical Circuits, Sept. 1991, p. 153) shows two configurations for linearized optical modulators for use in wide band analog transmission systems. Figure 4 shows an optical phase modulator formed by a cascaded Y-branch input, a first phase modulator, a first coupler, a second phase modulator, a second coupler and output waveguides. The figure also depicts bias electrodes for the phase modulators.

SUMMARY OF THE INVENTION

In accordance with one aspect of the present invention, there is provided an integrated optical phase modulator for modulating a light signal, comprising:

a substrate;

light signal receiving means for receiving and dividing a light signal into first and second light input signals of substantially equal power level;

first optical phase modulator means for receiving said first and second light input signals, and modulating the light input signals by a first rf signal, thereby producing modulated first and second complementary secondary output signals;

a first optical coupler having a pair of input ports for receiving said first and second secondary output signals, and a pair of output ports;

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second optical phase modulator means connected to said pair of output ports of said first optical coupler for receiving and then modulating said first and second secondary output signals by a second rf signal, thereby producing complementary third and fourth secondary output signals;

a second optical coupler having a pair of input ports for receiving said third and fourth secondary output signals and a pair of output ports;

first and second light waveguide means, each having an input port connected to first and second output ports, respectively, of said second optical coupler, each having an output port for providing complementary and linearized first and second modulated light output signals,

said light signal receiving means, first and second optical phase modulator means, first and second optical couplers, and first and second waveguide means, all being formed on said substrate; characterized by

means for compensating for deviations of coupling angle values of said first and second optical couplers, respectively, from predetermined values, said compensating means including

first and second impedance matching circuitry means connected between individual output terminals of said means for compensating and individual rf signal inputs of said first and second optical phase modulator means, respectively, for ensuring a flat and equal frequency response by said first and second optical phase modulator means to said first and second rf signals.

In accordance with another aspect of the present invention, there is provided a method for maximizing the linearity of an integrated optical phase modulator provided on a substrate, comprising the steps of:

forming a light splitting device, for splitting an input light signal into first and second input light signals;

forming a first optical phase modulator in cascade with said light splitting device for receiving said first

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and second input light signals and for producing first and second complementary output signals;

forming a first optical coupler in cascade with said first optical phase modulator;

forming a second optical phase modulator in cascade with said first optical coupler for receiving said first and second complementary output signals and for producing third and fourth complementary output signals via said first optical coupler;

forming a second optical coupler in cascade with said second optical phase modulator;

applying first and second rf modulating signals to said first and second optical phase modulators, respectively, for modulating said first and second input light signals, for producing first and second complementary output signals at output ports, respectively, of said second optical couplers, wherein

said first and second rf modulating signals being applied via impedance matching circuitry for ensuring a flat and equal frequency response by the first and second optical phase modulators.

In accordance with another aspect of the present invention, there is disclosed a cascaded integrated optical phase modulator for modulating a light signal, comprising:

a substrate;

receiving waveguide means for receiving a light input signal, and splitting said signal into first and second input light signals;

a first optical phase modulator including a first waveguide segment having one end connected to said receiving waveguide means for receiving said first input light signal, a second waveguide segment parallel to said first waveguide segment having one end connected to said receiving waveguide means for receiving said second input light signal, first and second modulating electrode means in parallel with and spaced apart from a portion of each one of said first and second waveguide segments, respectively, said first and second modulating electrode means being connected in common for receiving a first rf modulating signal, and first and

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second dc bias electrode means in parallel with and spaced apart from another portion of each one of said first and second waveguide segments, respectively, said first and second dc bias electrode means being connected in common for receiving a first dc bias voltage;

a first optical coupler including first and second parallel waveguide segments each having one end individually connected to another end of each one of said first and second waveguide segments, respectively, of said first optical phase modulator;

a second optical phase modulator including a first waveguide segment having one end connected to another end of said first waveguide segment of said first optical coupler a second waveguide segment parallel to said first waveguide segment having open end connected to another end of said second waveguide segment of said first optical coupler, said second optical phase modulator further including first and second modulating electrode means in parallel with and spaced apart from a portion of each one of said first and second modulating electrode means being connected in common for receiving a second rf modulating signal, and first and second dc bias electrode means in parallel with and spaced apart from another portion of each one of said first and second waveguide segments, respectively, said first and second dc bias electrode means being connected in common for receiving a second dc bias voltage;

a second optical coupler including first and second parallel waveguide segments each having one end individually connected to another end of each one of said first and second waveguide segments, respectively, of said second optical phase modulator;

output waveguide means connected individually to another end of each one of said first and second waveguide segments, respectively, of said second optical coupler, for providing first and second complementary light output signals, whereby the levels of said first and second dc bias voltages, and the amplitudes of at least one of said first and second rf modulating signals, are adjusted for

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maximizing the linearization of said first and second output signals;

said receiving waveguide means, first and second optical phase modulators, first and second optical couplers, and output waveguide means all being formed on said substrate; wherein

means for compensating for deviations of coupling angle values of said first and second optical couplers, respectively from predetermined values, said compensating means including

a source of first and second rf modulating signals; and

first and second impedance matching circuitry connected between individual output terminals of said source of first and second rf modulating signals, and said first and second optical phase modulators, respectively.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments of the present invention are illustrated below in conjunction with the accompanying drawings, wherein like items are identified by the same reference designation, and in which:

Figure 1 is a simplified pictorial diagram showing a linearized single coupler with one rf input;

Figure 2 is a plot or curve of the transfer function for optimized linear operation of the single coupler of Figure 1;

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Figure 3 is a simplified pictorial diagram of a phase modulator $\Delta\beta$ coupler cascade switch ~~for an embodiment of the invention~~;

Figure 4 is a curve showing the coupling angle γ as a function of rf weighting for the phase modulator of Figure 3;

Figure 5 is a curve showing the relative sensitivity as a function of rf weighting for the phase modulator of Figure 3;

Figure 6 is a curve showing a transfer function for the phase modulator-coupler cascade of Figure 3, for $\gamma = 45°$, and $k = -0.95$;

Figure 7 is a curve showing the third harmonic suppression (dB) as a function of modulation index m (dB) for the phase modulator-coupler cascade of Figure 3;

Figure 8 shows a simplified pictorial diagram of cascaded rf phase modulators of one embodiment of the invention;

Figure 9 is a curve showing the relative coupling angle ($\gamma/90$) as a function of rf weighting for the cascaded modulators of Figure 8;

Figure 10 is a curve showing the relative rf sensitivity as a function of rf weighting for the cascaded modulators of Figure 8;

Figure 11 is a curve showing a transfer function of the cascaded phase modulators of Figure 8 for $\gamma = 27°$ and $k = -0.5$;

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Figure 12 is a curve showing the third harmonic suppression as a function of modulating index m for the cascaded modulators of Figure 8;

Figure 13 shows a simplified pictorial diagram of cascaded rf phase modulators for another embodiment of the invention;

Figure 14 shows a simplified pictorial diagram of cascaded rf phase modulators for a preferred embodiment of the invention; and

Figure 15 shows a simplified schematic and pictorial diagram of an engineering prototype for the embodiment of Figure 14.

Detailed Description Of Preferred Embodiments Of The Invention

The linearized optical phase modulator embodiments of the present invention, as described below, may be considered linearized optical guided waveguide (OGW) modulators. In the various embodiments of the invention, each provides two complementary light output signals which offers advantages over prior modulators having only a single output signal. In the present embodiments of the invention, the complementary output signals are substantially of the same power level and are equally linear, thereby splitting the available laser power. Another advantage is that one of the complementary output signals may be used as a control signal, preferably in a closed loop system, for providing a bias adjustment to optimize and stabilize the linearity of the cascaded modulators.

In Figure 1, an improved linearized single coupler 1, having a single rf terminal 3 for receiving an rf input signal rf(x) is shown. Assuming an ideal coupler structure, coupler 1 includes two cascaded sections 5 and 7 having coupler lengths ℓ_1 and ℓ_2, respectively. An upper horizontal waveguide segment 9 conducts a light input signal a_{in} to a downward sloping waveguide segment 11 for providing an input laser light signal to the coupler 1. Also shown, but typically not used for providing a light signal to the coupler 1, is a lower horizontal waveguide segment 13, for conducting a light signal b_{in} into an upward sloping waveguide segment 15 for delivering the light signal b_{in} to coupler 1. The first coupler section 5 includes in the integrated structure shown a portion of a horizontal waveguide segment 17 for receiving light input signal a_{in} from waveguide segment 11, a portion of a lower waveguide segment 19 connected at one end to an output end of waveguide segment 15, an electrode 21 overlying an associated portion of waveguide 17, and an electrode 23 overlying an associated portion of waveguide 19. The terminal 3 is connected to electrode 21 for providing the rf signal rf(x) thereto, where x is an angular value representing the rf signal amplitude relative to the switching voltage. Electrode 23 is connected to a source of reference potential, ground in this example. Note that waveguides 17 and 19 are substantially parallel to one another as are electrodes 21 and 23.

The second coupler section 7 includes the remaining portions of waveguide segments 17 and 19, in this example. An electrode 25 overlies an associated portion of waveguide 17. An

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electrode 27 overlies an associated portion of waveguide 19. These elements are substantially parallel to one another. A bias terminal 29 is provided for connecting a DC bias voltage V_{dc} to electrode 25. Electrode 27 is connected to ground, in this example. A light output signal from the cascaded first and second coupler sections 5 and 7 is conducted from waveguide segment 17 through an upwardly sloping waveguide segment 31, and through a horizontal waveguide segment 33 to provide an a_{out} light output signal. Similarly, a light output signal b_{out} is conducted from the other end of waveguide segment 19 through a downwardly sloping waveguide segment 35, and following horizontal waveguide segment 37 to provide a b_{out} light output signal that is complementary to the a_{out} light output signal. As previously mentioned, these complementary light output signals a_{out} and b_{out} are substantially equally linear, and of the same power level. Note that the various waveguide segments are typically formed on a lithium niobate crystal substrate (not shown), with the waveguide segments 9, 11, 13, 15, 17, 19, 31, 33, 35, and 37 being formed by diffusing titanium into the substrate. The electrodes 21, 23, 25, and 27 are typically deposited on top of the substrate, and typically may consist of metals such as a first adhesion layer of chrome (typically 100 Angstroms thick), followed by a thick layer of aluminum (up to 10,000 Angstroms). Note also that the shape of any of the electrodes and waveguides illustrated in the various embodiments herein are not meant to

be limiting in that many shapes or configurations can be used therefor.

Assume that the coupler structure of Figure 1 is an ideal one and that the two cascaded sections 5 and 7 have coupling angles γ and γ_d, respectively, with no external voltages applied. Let the rf coupling be $\gamma \cdot x$. The two input-two output coupler 5,7 is described by its 2 x 2 transformation matrix M, as follows in equation (1):

$$\begin{pmatrix} a_{out} \\ b_{out} \end{pmatrix} = M \cdot \begin{pmatrix} a_{in} \\ b_{in} \end{pmatrix} \qquad (1)$$

where "a", "b" represent complex signal amplitudes of the parallel waveguides.

The rf section 5 transmission matrix is described as follows:

$$M_{rf} = \begin{vmatrix} \cos\phi + j\gamma x \sin\phi/\phi, & -j\gamma\sin\phi/\phi \\ -j\gamma\sin\phi/\phi, & \cos\phi - j\gamma x \sin\phi/\phi \end{vmatrix} \qquad (2)$$

where

$$j = \sqrt{-1}\ , \quad \phi = \gamma\sqrt{1+x^2}$$

x is proportional to the input signal voltage rf(x).

The dc bias section 7 is described as follows:

$$M_{dc} = \begin{vmatrix} \cos\phi_d + j\gamma_d q \sin\phi_d/\phi_d\ , & -j\gamma\phi_d\sin\phi_d/\phi_d \\ -j\gamma_d\sin\phi_d/\phi_d\ , & \cos\phi_d - j\gamma_d x\sin\phi_d/\phi_d \end{vmatrix} \qquad (3)$$

where ϕ_d is

$$\gamma_d\sqrt{1 + q^2}$$

q being proportional to the applied dc voltage.

To simplify calculations, equation 3 is rewritten as follows:

$$M_{dc} = \begin{vmatrix} \cos\alpha e^{j\beta}, & -j\sin\alpha \\ -j\sin\alpha, & \cos\alpha e^{-j\beta} \end{vmatrix} \quad (4)$$

where

$$\tan(\beta) = \frac{q}{\sqrt{1 + q^2}} \cdot \tan(\phi_d)$$

and

$$\sin(\alpha) = \frac{\sin(\phi_d)}{\sqrt{1 + q^2}}$$

The cascade coupling 5,7 is described as follows:

$$M_t = M_{dc} \cdot M_{rf} \quad (5)$$

with signal input a_{in}, $b_{in} = 0$, the signal transfer for output a_{out} is described by M_{11} as follows:

$$M_{t11} = \cos\alpha^{j\beta} \cdot (\cos\phi + j\,(\gamma x \cdot \sin\phi)/\phi) - (\sin\alpha \cdot \gamma \cdot \sin\phi)/\phi \quad (6)$$
$$= re + j \cdot im$$

where re, im represent the real and imaginary parts, respectively.

The output power proportional to the detected signal is as follows:

$$P/P_{in} = re^2 + im^2 = f(x) \quad (7)$$

The series expansion for f(x) is as follows:

$$f(x) = f(o) + df/dx(o) \cdot x + 1/2 \cdot d^2f/dx^2(o) \cdot x^2 + 1/6 \cdot d^3f/dx^3(o) \cdot x^3 + \ldots \quad (8)$$

In order to suppress second and third order distortion, the following relations are required:

$$d^2f/dx^2(o) = 0, \; d^3f/dx^3(o) = 0 \quad (9)$$

From equation (7) one can derive the following:

$$\begin{aligned} df/dx &= 2re \cdot re' + 2im \cdot im' \\ d^2f/dx^2 &= 2re'^2 + 2re \cdot re'' - 2im'^2 + 2im \cdot im'' \\ d^3f/dx^3 &= 6re' \cdot re'' + 2re \cdot re''' + 6im' \cdot im'' + 2im \cdot im''' \end{aligned} \quad (10)$$

where ', ", and "' denote first, second, third derivatives.

From equations (6) and (2), one can derive the following:

$$\begin{aligned} re'(0) &= 0 \\ re''(0) &= -\gamma \sin\gamma \cdot \cos\alpha - \sin\alpha \cdot \cos\beta \cdot (\gamma \cdot \cos\gamma - \sin\gamma) \\ re'''(0) &= 0 \\ im'(0) &= \sin\alpha \cdot \sin\beta \cdot \sin\gamma \\ im''(0) &= \sin\alpha \cdot \sin\beta (\gamma \cdot \cos\gamma - \sin\gamma) \\ im'''(0) &= 3 \cos\alpha (\gamma \cdot \cos\gamma - \sin\gamma) \end{aligned} \quad (11)$$

From equation (9) and (10), one obtains the following:

$$d^2f/dx^2(0) = (0) \quad (12)$$

From equation (12) it can be shown that:

$$\sin^2(\gamma)\cdot\sin(\alpha)\cdot\cos(\beta) = 0 \quad (13)$$

In addition if:

$$d^3f/dx^3(0) = (0)$$

then

$$\gamma - \tan\gamma = 0 \quad (14)$$

Solving for γ from equation (14), one obtains:
$\gamma = 2.86\cdot\pi/2 \sim \underline{257.4°}$

The modulator sensitivity is proportional to the following:

$$df/dx(0) = \sin^2(\alpha)\cdot\sin^2(\gamma)\cdot\sin(\beta) \quad (15)$$

A practical solution to equation (13) is therefore as follows:

$$\cos\beta = 0,\ \beta = \pi/2,\ 3\pi/2 \text{ etc.} \quad (16)$$

For maximum sensitivity:

$$\sin(2\alpha) = 1 \text{ or } \alpha = \pi/4 \quad (17)$$

From equation (3), one can obtain the following values:

$$\phi_d = \pi/2$$
$$\gamma_d = 1.11 \sim 63.6° \qquad q = 1.0 \quad (18)$$

A plot of a transfer function for optimized linear operation of the $\Delta\beta$ coupler of Figure 1 is shown in Figure 2, with $\gamma = 257.4°$, $\gamma_d = 63.6°$, and $q = 1.0$.

A phase modulator 41 in series with a $\Delta\beta$ coupler 43, as shown in Figure 3, provides a phase modulator $\Delta\beta$ cascade switch 45. An input light wave P_{in}, typically having a power level expressed in milliwatts, is applied to an input waveguide 47, for carrying the light wave P_{in} to be divided into upper

waveguide segment 49 and lower waveguide segment 8 of the Y-waveguide 47, 49, 51. Light from the upper segment 49 travels through a longitudinal upper waveguide segment 53, through an upper downward sloping waveguide segment 55, through an upper longitudinal and horizontal waveguide segment 61, through an upwardly sloping waveguide segment 69, and therefrom through a longitudinal end horizontal waveguide segment 73 for providing an output signal P_{out}. Similarly, lower waveguide segment 51 receives substantially half of the light signal P_{in} and conducts the same to travel through lower longitudinal and horizontal waveguide segment 57, therefrom through upward sloping waveguide segment 59, through lower horizontal waveguide segment 63, through downward sloping waveguide segment 71, and therefrom through lower horizontal waveguide segment 75, for providing from the latter a light output signal $\overline{P}_{out}$. $\overline{P}_{out}$ is complementary to the upper output signal P_{out}, in this example. A horizontal electrode 77 is both parallel and overlying to upper waveguide segment 53, for receiving via conductor 81 an rf input signal rf1. A lower electrode 79 is provided in parallel with and overlying the lower waveguide segment 57, as simplistically shown for purposes of illustration. Lower electrode 79 is connected to ground, in this example. The combination of waveguide segments 53 and 57, and electrodes 77 and 79, provide a phase modulator.

An electrode 65 is provided in parallel and overlying upper waveguide segment 61, and another electrode 67 is provided in parallel with and overlying lower waveguide segment 63. An electrode terminal 83 is provided for conducting to electrode 61

a second rf modulating signal rf2. Electrode 67 is connected to ground, in this example. The combination of waveguide segments 61 and 63, and electrodes 65 and 67 form a $-\Delta\beta$ coupler. Note that the length of the phase modulator section 41 is shown as a ℓ_1, whereas the $-\Delta\beta$ coupler 43 has a length ℓ_2.

Assuming an ideal, balanced configuration, rf electrodes 77, 79 with length ℓ_1 will generate a phase shift 2x between the two arms or waveguide segments 53 and 57 of phase modulator 41. The coupling angle of the $\Delta\beta$ coupler 43 is:

$$\Delta\beta = 2x' \tag{19}$$

where $x' = kx$.

The ratio $k = x'/x$ is proportional to the ratio of the two rf input signals rf_1 and rf_2 provided the electrode geometrics of electrodes 65 and 67, and associated impedance matching circuitry (not shown) are similar.

The phase modulator 41 transmission matrix is:

$$M_p = \begin{vmatrix} e^{jx}, 0 \\ 0, e^{-jx} \end{vmatrix} \tag{20}$$

The $-\Delta\beta$ coupler section 43 matrix is as follows:

$$M_c = \begin{vmatrix} \cos\phi + jx'\sin\phi/\phi, & -j\gamma\sin\phi/\phi \\ -j\gamma\sin\phi/\phi, & \cos\phi - jx'\sin\phi/\phi \end{vmatrix} \tag{21}$$

where

$$\phi = \sqrt{\gamma^2 + x'^2}$$

The total matrix is then as follows:

$$M_t = \begin{vmatrix} e^{jx}(\cos\phi + jx'\sin\phi/\phi), & -je^{-jx}\gamma\sin\phi/\phi \\ -je^{jx}\gamma\sin\phi/\phi, & e^{-jx}(\cos - jx'\sin\phi/\phi \end{vmatrix} \quad (22)$$

The output power is:

$$f(x) = (P_{out} + \bar{P}_{out})/P_{in} = 1/2\ |mt_{11} + mt_{12}|^2 \quad (23)$$

From equation (22):

$$mt_{11} + mt_{12} = \cos x \cdot \cos\phi - \sin\gamma\ \sin\phi/\phi - x'\sin x \cdot \sin\phi/\phi + (\sin x \cdot \cos x'\cos x \cdot \sin\phi/\phi - \gamma\ \cos x \cdot (\sin\phi)/\phi) \quad (24)$$

By substitution into equation (23):

$$f(x) = 0.5 - \sin\phi/\phi \cdot (\sin(2x)\ \cos\phi + x' \cdot \cos(2x) \cdot \sin\phi/\phi) \quad (25)$$

By successive derivation of f(x) with respect to x, one obtains:

$$\text{sensitivity } df/dx(0) = -\sin(2\gamma) - 0.5 \cdot k(1-\cos(2\gamma))/\gamma \quad (26)$$

Second order distortion is expressed as follows:

$$d^2f/dx^2(0) = 0 \text{ for all values of } k, \gamma \text{ (no bias)} \quad (27)$$

Third order distortion is as follows:

$$d^3f/dx^3(0) = 0 \text{ for } k^3 + a_2k^2 + a_1k + a_0 = 0 \quad (28)$$

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where

$$a_0 = -4\sin(2\gamma)\cdot\gamma^3/3\cdot(\gamma\sin(2\gamma) + \cos(2\gamma)-1)^{-1}$$

$$a_1 = -2(1-\cos(2\gamma))\cdot\gamma^2\cdot(\gamma\sin(2\gamma) + \cos(2\gamma)-1)^{-1} \quad (29)$$

$$a_2 = -(2\gamma\cos(2\gamma)-\sin(2\gamma)\gamma\cdot(\gamma\sin(2\gamma) + \cos(2\gamma)-1)^{-1}$$

From (28) and (26) the coupling angle γ and the sensitivity df/dx (0) for third order distortion compensation can be found as function of the rf weighting k.

Results from these calculations are shown in Figures 4 and 5, for curves showing coupling angle γ as a function of rf weighting, and relative sensitivity df/dx as a function of rf weighting, respectively.

It appears from Figure 5, that a reasonable sensitivity is obtained for weighting factors in the range of -0.5 to 1.5. Corresponding ranges for coupling angles are 45° to 65° and 105° to 140°. Consider as an example, γ = 45°. The calculated transfer function is shown in Figure 6 as a plot of relative input intensity as a function of relative input signal. Figure 7 shows relative harmonic distortion as a function of modulation index m.

In Figure 8, an~~other~~ embodiment of the invention is shown for cascading two phase modulators 85 and 87 with two fixed couplers 89 and 91. In comparison with the modulator ~~embodiment~~ of Figure 3, each receives two input signals rf1 and rf2, for example, but a $\Delta\beta$ coupler region such as 43 is avoided in the embodiment of Figure 8.

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Phase modulators 85 and 87 have similar structure as phase modulator 41. One difference is that phase modulator 87 is configured for receiving via input electrode 81 the rf input signal rf2, and waveguide segments 49 and 51 receive complementary light signals from a coupler 89.

Also, in modulators 85 and 87, relative to modulator 41, electrodes 77 and 79 are located between, proximate, and parallel to waveguide segments 53 and 57, respectively, and electrically connected together by bridging electrode 82. Electrodes 88 and 86 are located proximate and in parallel with the other sides of waveguide segments 53 and 57, as shown in this example. Electrodes 88 and 86 are connected to a source of reference potential, ground in this example.

The fixed coupler 89 has a length ℓ_c, and includes two parallel waveguide segments 93,95, for coupling output waveguide segment 55 to input waveguide segment 49, and output waveguide 59 to input waveguide segment 51, of phase modulators 85 and 87, respectively. Fixed coupler 91 is substantially similar to coupler 89, and consists of parallel waveguide segments 97 and 99 for coupling output waveguide segments 55 and 59, respectively, from phase modulator 87, to upward and downwardly sloping waveguide segments 101 and 103, respectively, in this example. Waveguide segments 101 and 103 have their other ends connected to an end of upper and lower horizontal and parallel waveguide segments 105 and 107, respectively. The other ends of the waveguide segments 105 and 107 provide complementary modulated light output signals P_{out} and $\overline{P}_{out}$, respectively. Note

that phase modulators 85 and 87 have lengths of ℓ, and ℓ_2, respectively, wnich are typically substantially equal.

In the embodiment of Figure 8, the total transmission matrix consists of four cascaded section matrices as given below in equations (30), (31) and (32). Assume the fixed couplers 89 and 91 have identical coupling, their transmission matrix M_c is as follows in equation (30):

$$M_c = \begin{vmatrix} \cos\gamma, -j\sin\gamma \\ -j\sin\gamma, \cos\gamma \end{vmatrix} \qquad (30)$$

Rf phase modulator 85 has a transmission matrix M_{P1} as follows:

$$M_{P1} = \begin{vmatrix} e^{jx}, 0 \\ 0, e^{-jx} \end{vmatrix} \qquad (31)$$

Note that 2x, obtained in solving the matrix M_{P1}, is the phase difference in the two arms.

Similarly, for the second phase modulator 87, its transmission matrix is M_{P2} as follows in equation (32):

$$M_{P2} = \begin{vmatrix} e^{jx'}, 0 \\ 0, e^{-jx'} \end{vmatrix} \qquad (32)$$

where $x' = kx$, and k = rf weighting factor.

The total matrix is the sum of the individual matrices as shown below in equation (33):

$$M_t = M_C M_{P2} M_C M_{P1} \quad (33)$$

Accordingly, M_t can be expressed as shown below in equation (34):

$$M_c = \begin{vmatrix} \cos^2\gamma e^{j\psi_1} - \sin^2\gamma e^{j\psi_2}, & -j\sin\gamma\cos\gamma\,(e^{-j\psi_1} + e^{-j\psi_2}) \\ -j\,\sin\gamma\cos\gamma\,(e^{j\psi_1} + e^{j\psi_2}), & \cos^2\gamma e^{-j\psi_1} - \sin^2\gamma e^{-j\psi_2} \end{vmatrix} \quad (34)$$

where $\psi_1 = x+x'$ and $\psi_2 = x-x'$.

The relative output power is as follows in equation (35):

$$F(x) = P/P_{in} = 1/2\ (re^2+im^2) \quad (35)$$

where

$$re = \cos^2\gamma\cdot\cos\psi_1 - \sin^2\gamma\cdot\cos\psi_2 - \sin\gamma\ \cos\gamma\ (\sin\psi_1 + \sin\psi_2),$$

and

$$im = \cos^2\gamma\cdot\cos\psi_1 - \sin^2\gamma\ \sin\ \psi_2 - \sin\gamma\cdot\cos\gamma\ (\cos\psi_1 + \cos\psi_2).$$

From successive derivation:

$$\text{Sensitivity } df/dx(0) = -\sin(2\gamma)(2\cos(2\gamma)+k) \quad (36)$$

Second order distortion is expressed by:

$$d^2f/dx^2(0) = 0 \text{ for all values of } k,\gamma(\text{no bias}) \quad (37)$$

Third order distortion is expressed by:

$$d^3f/dx^3(0) = 0 \text{ for } k^3+3\cos(2\gamma)k^2+3k+2\cos(2\gamma) = 0 \quad (38)$$

From equations (36) and (38) the coupling angle γ and the sensitivity df/dx(0) for third order compensation can be determined as a function of rf weighting. Results are shown in Figures 9 and 10, for plots showing (γ/90) as a function of rf weighting, and rf sensitivity as a function of rf weighting, respectively.

Figure 10 shows that an optimum operating point in terms of rf sensitivity is obtained if $k \approx -0.5$. This corresponds to a coupling range γ of $0.3(90°) = 27°$. The calculated transfer function for this case is shown in Figure 11, for relative input intensity as a function of relative input signal. The corresponding suppression of third harmonic generation as function of modulation index m is shown in Figure 12.

In evaluating switch modulators with regard to practical implementation, from the standpoint of simplicity in both design and rf feeding circuitry, the ~~embodiment of the invention~~ modulator of Figure 1 ($\Delta\beta$ coupler with one rf-input) looks most attractive. However, certain drawbacks for a practical implementation would be:

1. The simple theory described allows for no bias adjustment to compensate for fabrication errors and imperfect behavior. In reality, additional fixed coupling regions outside the electrodes will be present, as well as asymmetries due to fabrication errors. Conceivably, these factors could be taken into account in a more sophisticated model. It is

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anticipated that by using additional bias electrodes, a good compensation of second and third order distortions could be obtained.

2. The optimum coupling angle is rather large (γ = 257°) which could make the overall device rather sensitive to fabrication errors. In general, the detailed behavior of multi-electrode couplers are somewhat more difficult to control than simple phase modulators.

The ~~second alternative embodiment~~ modulator of Figure 3 is slightly more complex than the embodiment of Figure 1 in that the former requires two rf electrodes, 81 and 83, which have to be properly weighted, including external adjustments of signal amplitudes for modulating rf signals rf1 and rf2. Fabrication errors and additional fixed coupling regions can be adjusted for by using additional bias electrodes in both cascaded sections.

The ~~third alternative~~ invention embodiment of Figure 8 has an apparent disadvantage in a slightly longer total waveguide structure, which could mean slightly increased throughput loss. However, with reasonable fabrication accuracy, it is expected that fine tuning of the coupler regions, 89 and 91, will not be necessary. Fabrication errors and modest environmental instabilities can be easily handled by adjusting dc voltages at bias electrodes 81 in the two phase modulator sections 85 and 87.

The embodiment of the invention of Figure 8 can be modified as shown in Figure 13 for substituting a 3 dB coupler for the Y-branch power splitter formed by waveguide segments 47,

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49, and 51 at the input of phase modulator 85. In this embodiment, the 3 dB coupler 109 includes an input waveguide segment 111 for receiving a light input signal P_{in}, and guiding the same to a downward sloping waveguide segment 113 connected successively in series with a horizontal waveguide segment 114, and an upward sloping waveguide segment 117, the latter feeding an input signal into the upper waveguide segment 53 of phase modulator 85. Similarly, coupler 109 includes lower waveguide segments successively connected in series including an input segment 119, an upward sloping segment 121, a horizontal segment 123 parallel to the upper horizontal waveguide segment 114, and a downward sloping segment 125 connected to the lower horizontal waveguide segment 57 of phase modulator 85. Note that the modulator structure is fabricated on a substrate 112. The signal transfer function for relative power output of the modulator for this alternative embodiment is shown in equation (36). Equations (37) and (38) also are applicable to this embodiment of the invention.

In Figure 14, another embodiment of the invention that is a modification of the embodiment of Figure 8, includes for phase modulator 85 the addition of dc bias electrode 135 parallel to a portion of waveguide segment 53, and bias electrodes 137 parallel to a portion of waveguide segment 57, with ground plane electrodes 139 and 141 added in parallel to bias electrodes 135 and 137, respectively. In addition, a bias electrode 143, for receiving a dc bias voltage V_{DC1}, is connected in common to bias electrodes 135 and 137. Similarly, for phase modulator 87, bias

electrodes 135 and 137 have been added in parallel with ground electrodes 139 and 141, respectively, on either side of waveguide segments 53 and 57, respectively. However, input electrode 143 of phase modulator 87 provides for the connection to a dc bias voltage V_{DC2} rather than V_{DC1} as in phase modulator 85. Further, a modulating voltage V(t) is provided to a power splitter 145, such as a Y-branch power splitter, for splitting the input signal V(t) into two substantially equal rf signals $V_1(t)$ and $V_2(t)$, for connection to the input terminals of variable rf attenuators 147 and 149, respectively. The output of variable attenuator 147 is connected to the input of impedance matching circuitry 151, the output of the latter providing rf signal rf1 to electrode 81 of phase modulator 85. Similarly, impedance matching circuitry 153 is included for receiving the output signal from attenuator 149 for providing rf modulating signal rf2 to electrode 81 of phase modulator 87. The modulator structure of Figure 14 is a practical implementation with low switching or modulating voltage. Due to fabrication inaccuracies, the coupling angle γ for couplers 89 and 91, respectively, may deviate from intended design values. With the embodiment of Figure 14, errors due to such fabrication inaccuracies are compensated for by using variable attenuators 147 and 149 to adjust the amplitudes of the rf signals applied to matching circuits 151 and 153. Also, fabrication errors may cause asymmetric phase modulation, which is compensated for in this embodiment by adjusting the levels of the dc-bias voltages V_{DC1} and V_{DC2} through use of adjustable DC voltage supplies (not shown), for example. Further note that the

external matching circuitry 151 and 153 provides for insuring a flat and equal frequency response for rf input signals rf1 and rf2, by phase modulators 85 and 87, respectively. Note further that the level of the light input signal P_{in} is typically in the range of 10 to 100 millivolts, and the rf modulating signal V(t), is typically is 0 to 10 dBm for a cable TV signal, for example.

In Figure 15, a linearized modulator prototype design is shown, that is related to the simplified configuration of the modulator of Figure 14. Similar items between the two figures are indicated by the same reference designation.

As shown in Figure 15, the linearized modulator 84 includes an input waveguide in the form of a Y-splitter 172, for receiving and splitting a light input signal P_{in}, and guiding the split light signals into elongated waveguides 53 and 57, respectively, of phase modulator 85. The fixed coupler 89 couples the output light signals from waveguides 53 and 57 to the like waveguides 53 and 57, respectively, of phase modulator 87. The output light signals from phase modulator 87 are coupled by fixed coupler 91 to output waveguides 201 and 203, respectively, for providing complementary P_{out} and $\bar{P}_{out}$ modulated and linearized light output signals, respectively. In this configuration, ground plane or RFI electrodes 173, 175, and 177, are generally rectangular in shape, successively juxtaposed from one another, and overlie the elongated parallel waveguides 53 and 57, of the associated phase modulators 85, 87, respectively, as shown. The parallel and opposing longer sides of each of the RFI electrodes 173, 175, 177 are positioned to be parallel to the waveguides 53

and 57, and on the outside thereof, in this example. Centrally located openings 174, 187, 189, are formed in a like elongated side of each one of the RFI electrodes 173, 175, 177, respectively, for permitting the leg portions of T-shaped electrodes 181, 185, and 193, respectively, to pass therethrough. As shown, for each of the T-shaped electrodes 181, 185, 193, the top associated narrow electrode portions are positioned parallel to and between waveguides 53 and 57, and within the rectangular area formed by the RFI electrodes 173, 175, and 177, as shown. The T-shaped electrodes 181, 185, and 193, have their leg portions terminating at and connected to connection or terminals pads 179, 183 and 191, respectively.

For each of the phase modulators 85 and 87, the RFI electrodes 173, 175, and 177, are connected to a source of reference potential, ground in this example. Phase modulator 85 has connection or terminal pads 179 and 183 connected to impedance matching circuit 151 for receiving a portion of a modulating signal rf1. Terminal pad 191 is connected to receive the DC bias voltage V_{DC1}. Similarly, phase modulator 87 has terminal pads 179 and 183 connected to impedance matching circuit 153 for receiving an rf modulating signal rf2, and terminal pad 191 is connected to receive DC bias voltage V_{DC2}.

Impedance matching circuits 151 and 153 include three inductors 165, 167 and 169, connected in series with a load resistor 171. One end of the load resistor 171 is connected to a source of reference potential, ground in this example. The other end of inductor 165 of matching circuit 151 is connected

to receive modulating signal rf1. Similarly, the other end of inductor 165 of matching circuit 153 is connected to receive another modulating signal rf2. In matching circuit 151, the common connection between inductors 165 and 167 is connected to terminal pad 179 of modulator stage 85, and the connection between inductors 167 and 169 is connected to terminal pad 183 of modulator stage 85. In matching circuit 153, the common connection between inductors 165 and 167 is connected to terminal pad 179 of modulator stage 87, and the common connection between inductors 167 and 169 is connected to terminal pad 183 of modulation stage 87.

RF input signal V(t) is connected to a power splitter 145. One output signal from splitter 145 provides modulating signal rf1 to matching circuit 151. The other output signal from power splitter 145 is connected through an adjustable delay circuit 161 to adjustable amplitude control circuit 163. The output signal from the adjustable amplitude control circuit 163 provides modulating signal rf2 to matching circuit 153.

In the linearized modulator of Figure 15, the RFI electrodes 173 and 175 are, in this example, divided into two separate configurations to facilitate electrical or impedance matching to the characteristic impedance of load resistor 171 in the associated matching circuit 151 or 153. Also in this manner, resistive losses in the electrode structures for electrodes 173 and 175 are minimized. Alternatively, but less preferred, a single electrode structure could be utilized in place of electrodes 173 and 175 in the form of a traveling wave

configuration. However, for the latter configuration, thicker electrodes would be required relative to the preferred configuration, in order to reduce electrode resistive losses. Also, for the latter configuration, an impedance transformer or additional resistor may be required in each of the impedance matching circuits 151 and 153. Note also that to obtain the desired characteristic impedance for the matching circuits 151 and 153, the value of inductor 167 is typically twice the inductance of inductors 165 and 169, with the values being chosen to match the capacitance of the electrodes of phase modulators 85 and 87, respectively, for obtaining the correct characteristic impedance for matching circuits 151 and 153, respectively. Inductors 165, 167, 169 can be provided by high-impedance transmission lines stubs connected with bond wires in a printed circuit board layout, for example.

The power splitter 145 can be provided by a wide-band hybrid transformer, or in the application of in-phase feeding of the rf electrodes 181 and 183, respectively, a resistive power splitting network can be used. Adjustable delay circuit 161 can be provided by an all pass discrete component network with variable components, or by a folded transmission line with adjustable band connections. The adjustable amplitude circuit 163 can be provided by any commonly available variable attenuator, or from a resistive network with variable components, as would be known to one of skill in the art.

Although various embodiments of the invention have been illustrated and described herein, they are not meant to be

limiting. Those skilled in the art may recognize modifications to these various embodiments, which modifications are meant to be covered by the ~~spirit and~~ scope of the appended claims.

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The claims defining the invention are as follows:-

1. An integrated optical phase modulator for modulating a light signal, comprising:

a substrate;

light signal receiving means for receiving and dividing a light signal into first and second light input signals of substantially equal power level;

first optical phase modulator means for receiving said first and second light input signals, and modulating the light input signals by a first rf signal, thereby producing modulated first and second complementary secondary output signals;

a first optical coupler having a pair of input ports for receiving said first and second secondary output signals, and a pair of output ports;

second optical phase modulator means connected to said pair of output ports of said first optical coupler for receiving and then modulating said first and second secondary output signals by a second rf signal, thereby producing complementary third and fourth secondary output signals;

a second optical coupler having a pair of input ports for receiving said third and fourth secondary output signals and a pair of output ports;

first and second light waveguide means, each having an input port connected to first and second output ports, respectively, of said second optical coupler, each having an output port for providing complementary and linearized first and second modulated light output signals,

said light signal receiving means, first and second optical phase modulator means, first and second optical couplers, and first and second waveguide means, all being formed on said substrate, wherein:

means for compensating for deviations of coupling angle values of said first and second optical couplers, respectively, from predetermined values, said compensating means including

first and second impedance matching circuitry means connected between individual output terminals of said means

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for compensating and individual rf signal inputs of said first and second optical phase modulator means, respectively, for ensuring a flat and equal frequency response by said first and second optical phase modulator means to said first and second rf signals.

2. The integrated optical phase modulator of claim 1, wherein said light signal receiving means consists of a Y-branch power splitter.

3. The integrated optical phase modulator of claim 1, wherein said light signal receiving means consists of a 3 dB coupler.

4. The integrated optical phase modulator of claim 1, further including means for compensating for asymmetric phase modulation in each of said first and second optical phase modulator means.

5. The integrated optical phase modulator of claim 4, wherein said means for compensating for asymmetric phase modulation includes dc bias electrode means in each one of said first and second optical phase modulator means, for receiving first and second dc bias voltages, respectively, whereby the levels of said first and second dc bias voltages are adjusted relative to one another for providing compensation for the asymmetric phase modulation.

6. The integrated phase modulator of claim 1, wherein said means for compensating for deviations of coupling angle values includes means for individually adjusting the amplitude of at least one of said first and second rf signals.

7. The integrated phase modulator of claim 6, wherein said means for individually adjusting includes:

a power splitter for receiving an rf signal V(t), and splitting the rf signals V(t) into two substantially equal rf signal $V_1(t)$ and $V_2(t)$; and

first and second variable attenuators for receiving said $V_1(t)$ and $V_2(t)$ rf signals, respectively, for selectively adjusting the amplitudes of these rf signals, thereby producing said first and second rf signals.

8. An integrated optical phase modulator according to any one of the preceding claims wherein said first and

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second optical phase modulator stages include first and second elongated, parallel and spaced apart waveguides, first through third juxtaposed radio-frequency-interference (RFI) electrodes each having an elongated rectangular shape with a centrally located elongated opening, each overlying and centered upon said first and second waveguides, first through third signal electrodes centrally located between and parallel with said first and second waveguides within the respective opening of said rectangular configured RFI electrodes, respectively, first through third electrical terminal pads located outside of said first through third RFI electrodes, respectively, and first through third connecting electrodes for connecting said first through third terminal pads to said first through third signal electrodes respectively, through openings in side members of said first through third RFI electrodes, respectively;

whereby said first and second waveguides of said first phase modulator stage being connected for receiving said first and second light input signals;

said RFI electrodes of said first and second phase modulator stages each being connected to a source of reference potential;

said first and second terminal pads of said first phase modulator stage each being adapted for receiving a first modulating signal;

said first and second terminal pads of said second phase modulator stage each being adapted for receiving a second modulating signal;

said third terminal pads of said first and second phase modulator stages being adapted for receiving first and second dc bias voltages respectively; and

a substrate upon which said linearized cascaded optical phase modulator is formed.

9. A method for maximizing the linearity of an integrated optical phase modulator provided on a substrate, comprising the steps of:

forming a light splitting device, for splitting an input light signal into first and second input light signals;

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forming a first optical phase modulator in cascade with said light splitting device for receiving said first and second input light signals and for producing first and second complementary output signals;

forming a first optical coupler in cascade with said first optical phase modulator;

forming a second optical phase modulator in cascade with said first optical coupler for receiving said first and second complementary output signals and for producing third and fourth complementary output signals via said first optical coupler;

forming a second optical coupler in cascade with said second optical phase modulator;

applying first and second rf modulating signals to said first and second optical phase modulators, respectively, for modulating said first and second input light signals, for producing first and second complementary output signals at output ports, respectively, of said second optical couplers, wherein

said first and second rf modulating signals being applied via impedance matching circuitry for ensuring a flat and equal frequency response by the first and second optical phase modulators.

10. The method of claim 9, further including the step of adjusting the levels of at least one of said first and second rf modulating signals, for compensating for deviations in the coupling angles of said first and second optical couplers.

11. The method of claim 9, further including the step of:

forming dc bias electrodes on said first and second optical phase modulators; and

applying and adjusting the levels of first and second dc bias voltages to said dc bias electrodes of said first and second phase modulators, respectively, for compensating for asymmetric phase modulation.

12. A cascaded integrated optical phase modulator for modulating a light signal, comprising:

a substrate;

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receiving waveguide means for receiving a light input signal, and splitting said signal into first and second input light signals;

a first optical phase modulator including a first waveguide segment having one end connected to said receiving waveguide means for receiving said first input light signal, a second waveguide segment parallel to said first waveguide segment having one end connected to said receiving waveguide means for receiving said second input light signal, first and second modulating electrode means in parallel with and spaced apart from a portion of each one of said first and second waveguide segments, respectively, said first and second modulating electrode means being connected in common for receiving a first rf modulating signal, and first and second dc bias electrode means in parallel with and spaced apart from another portion of each one of said first and second waveguide segments, respectively, said first and second dc bias electrode means being connected in common for receiving a first dc bias voltage;

a first optical coupler including first and second parallel waveguide segments each having one end individually connected to another end of each one of said first and second waveguide segments, respectively, of said first optical phase modulator;

a second optical phase modulator including a first waveguide segment having one end connected to another end of said first waveguide segment of said first optical coupler, a second waveguide segment parallel to said first waveguide segment having one end connected to another end of said second waveguide segment of said first optical coupler, said second optical phase modulator further including first and second modulating electrode means in parallel with and spaced apart from a portion of each one of said first and second modulating electrode means being connected in common for receiving a second rf modulating signal, and first and second dc bias electrode means in parallel with and spaced apart from another portion of each one of said first and second waveguide segments, respectively, said first and

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second dc bias electrode means being connected in common for receiving a second dc bias voltage;

a second optical coupler including first and second parallel waveguide segments each having one end individually connected to another end of each one of said first and second waveguide segments, respectively, of said second optical phase modulator;

output waveguide means connected individually to another end of each one of said first and second waveguide segments, respectively, of said second optical coupler, for providing first and second complementary light output signals, whereby the levels of said first and second dc bias voltages, and the amplitudes of at least one of said first and second rf modulating signals, are adjusted for maximizing the linearization of said first and second output signals;

said receiving waveguide means, first and second optical phase modulators, first and second optical couplers, and output waveguide means all being formed on said substrate; wherein

means for compensating for deviations of coupling angle values of said first and second optical couplers, respectively, from predetermined values, said compensating means including

a source of first and second rf modulating signals; and

first and second impedance matching circuitry connected between individual output terminals of said source of first and second rf modulating signals, and said first and second optical phase modulators, respectively.

13. The cascaded integrated optical phase modulator of claim 12, wherein said first optical phase modulator further includes:

first and second reference voltage electrodes in parallel with said first and second modulating electrodes, respectively, with said first and second waveguide segments lying therebetween, respectively; and

third and fourth reference voltage electrodes in parallel with first and second dc bias electrode means,

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respectively, with said first and second waveguide segments lying therebetween, respectively, whereby said first through fourth reference voltage electrodes are each receptive of a reference voltage.

14. The cascaded integrated optical phase modulator of claim 13, wherein said second optical phase modulator further includes:

first and second reference voltage electrodes in parallel with said first and second modulating electrodes, respectively, with said first and second waveguide segments lying therebetween, respectively; and

third and fourth reference voltage electrodes in parallel with first and second dc bias electrode means, respectively, with said first and second waveguide segments lying therebetween, respectively, whereby said first through fourth reference voltage electrodes are each receptive of a reference voltage.

15. The cascaded integrated optical phase modulator of claim 12, further including a source of adjustable first and second rf modulating signals including:

a splitter for receiving and splitting an rf voltage signal into first and second rf modulating signals; and

at least one variable attenuator for selectively controlling the amplitude of at least one of said first and second rf modulating signals, for compensating for errors in the coupling angles of said first and second optical couplers.

16. The cascaded integrated optical phase modulator of claim 12, wherein said receiving waveguide means consists of a Y-branch power splitter.

17. The cascaded integrated optical phase modulator of claim 12, wherein said receiving waveguide means consists of a 3 dB optical coupler.

18. An integrated optical phase modulator substantially as herein described with reference to Figs. 1 and 2.

19. An integrated optical phase modulation substantially as herein described with reference to Figs. 3 to 7 of the accompanying drawings.

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20. An integrated optical phase modulator substantially as herein described with reference to Figs. 8 to 12.

21. An integrated optical phase modulator substantially as herein described with reference to Fig. 13.

22. An integrated optical phase modulator substantially as herein described with reference to Figs. 14 and 15.

23. A method of maximizing the linearity of an integrated optical phase modulator provided on a substrate, substantially as herein described with reference to Figs. 1 and 2.

24. A method of maximizing the linearity of an integrated optical phase modulator provided on a substrate, substantially as herein described with reference to Figs. 3 to 7.

25. A method of maximizing the linearity of an integrated optical phase modulator provided on a substrate, substantially as herein described with reference to Figs. 8 to 12.

26. A method of maximizing the linearity of an integrated optical phase modulator provided on a substrate, substantially as herein described with reference to Fig. 13.

27. A method of maximizing the linearity of an integrated optical phase modulator provided on a substrate, substantially as herein described with reference to Figs. 14 and 15.

DATED this Seventeenth Day of January 1997

Crystal Technology, Inc.

Patent Attorneys for the Applicant/Nominated Person

SPRUSON & FERGUSON

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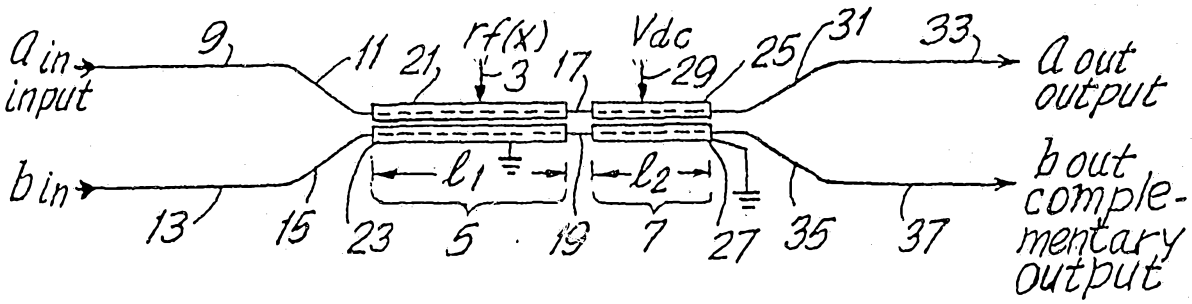

FIG.1

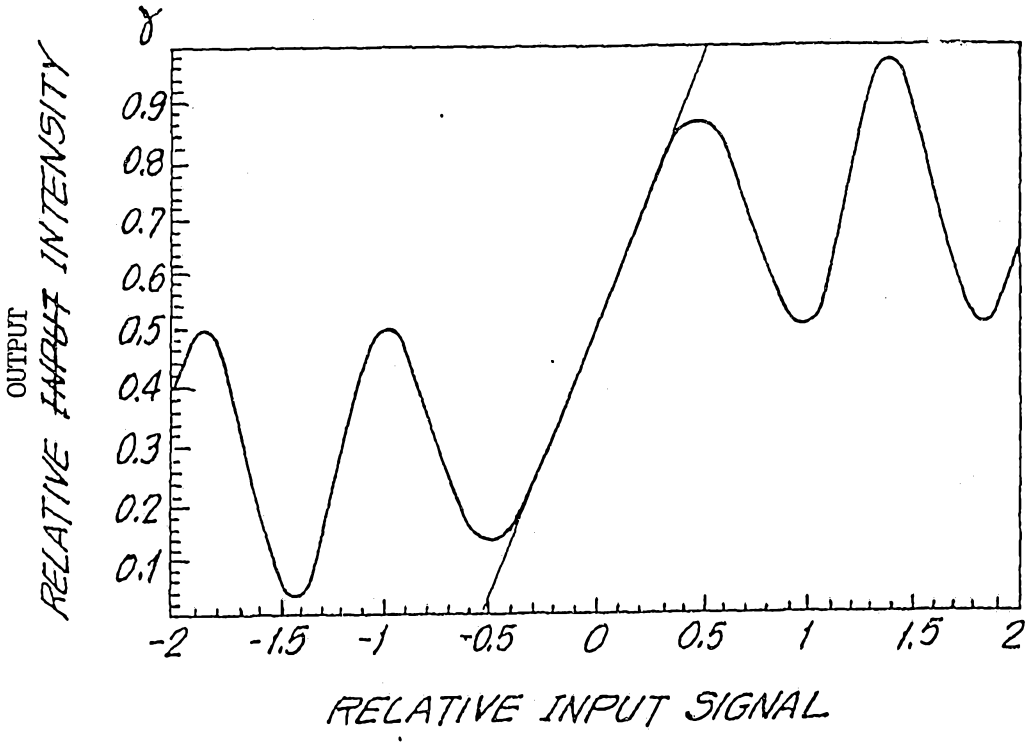

FIG.2

AMENDED SHEET

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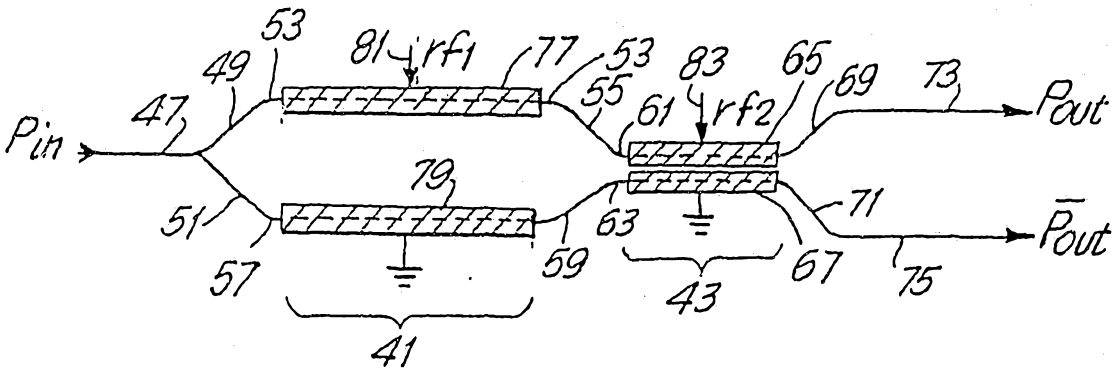
53
81
rf1
77
53
83
65
69
73
49
47
55
61
rf2
Pout
Pin
79
71
51
63
$\bar{P}$out
57
59
67
75
43
41

FIG.3

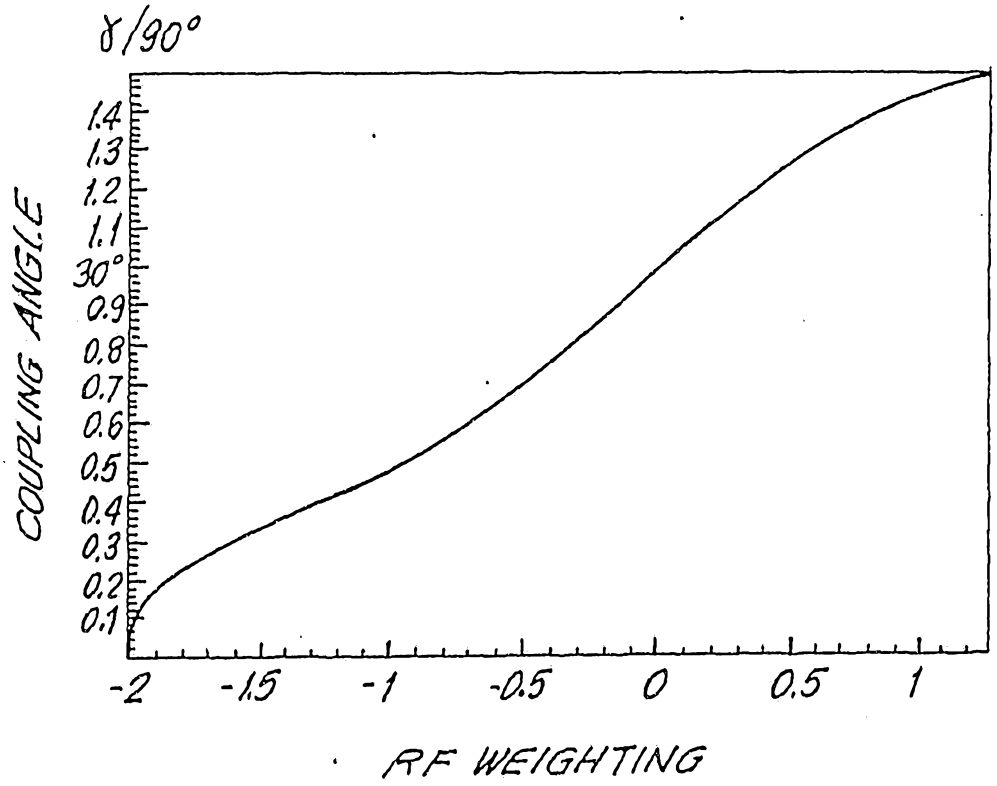
δ/90°
1.4
1.3
1.2
1.1
30°
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
COUPLING ANGLE
-2
-1.5
-1
-0.5
0
0.5
1
RF WEIGHTING

FIG.4

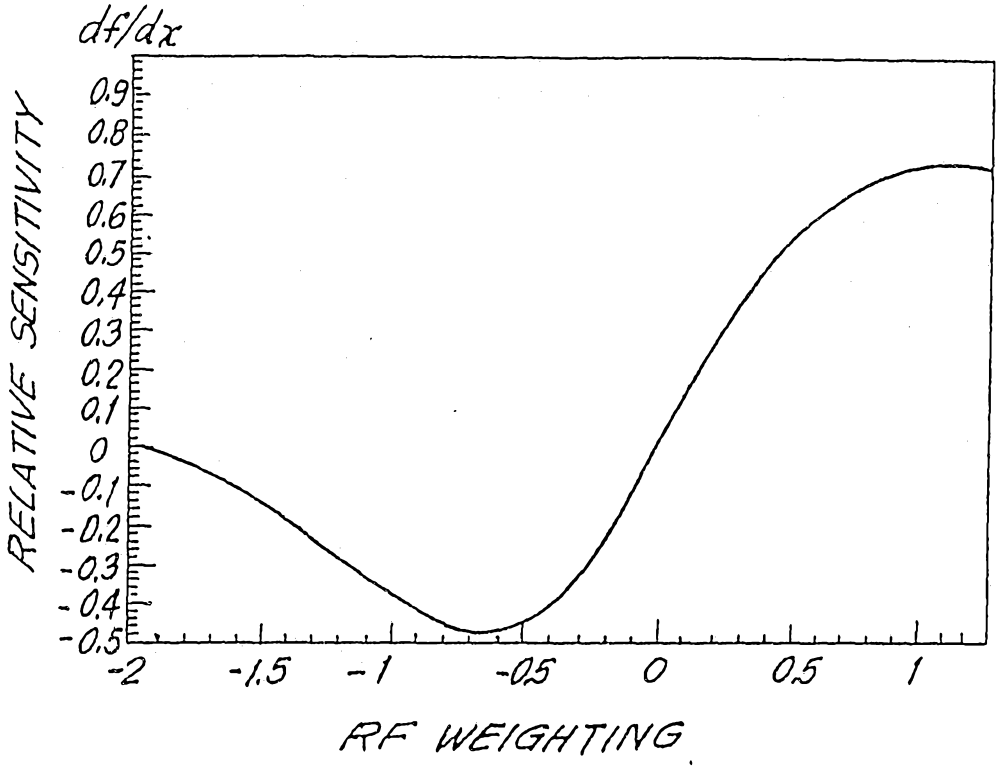
df/dx
RELATIVE SENSITIVITY
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-2
-1.5
-1
-0.5
0
0.5
1
RF WEIGHTING

FIG.5

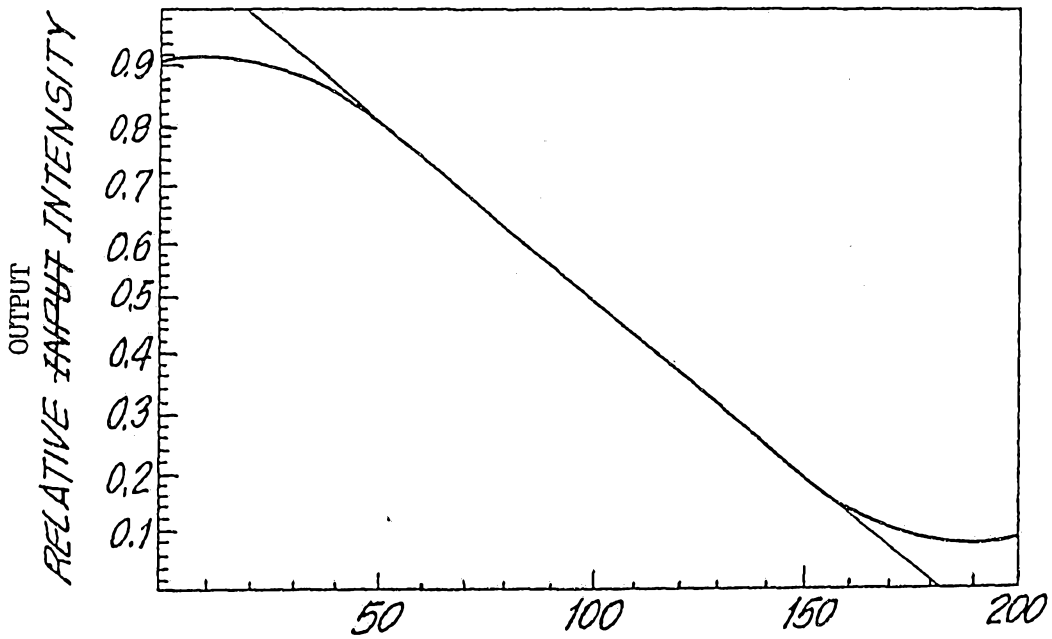
OUTPUT
RELATIVE INTENSITY
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
50
100
150
200
RELATIVE INPUT SIGNAL

FIG.6

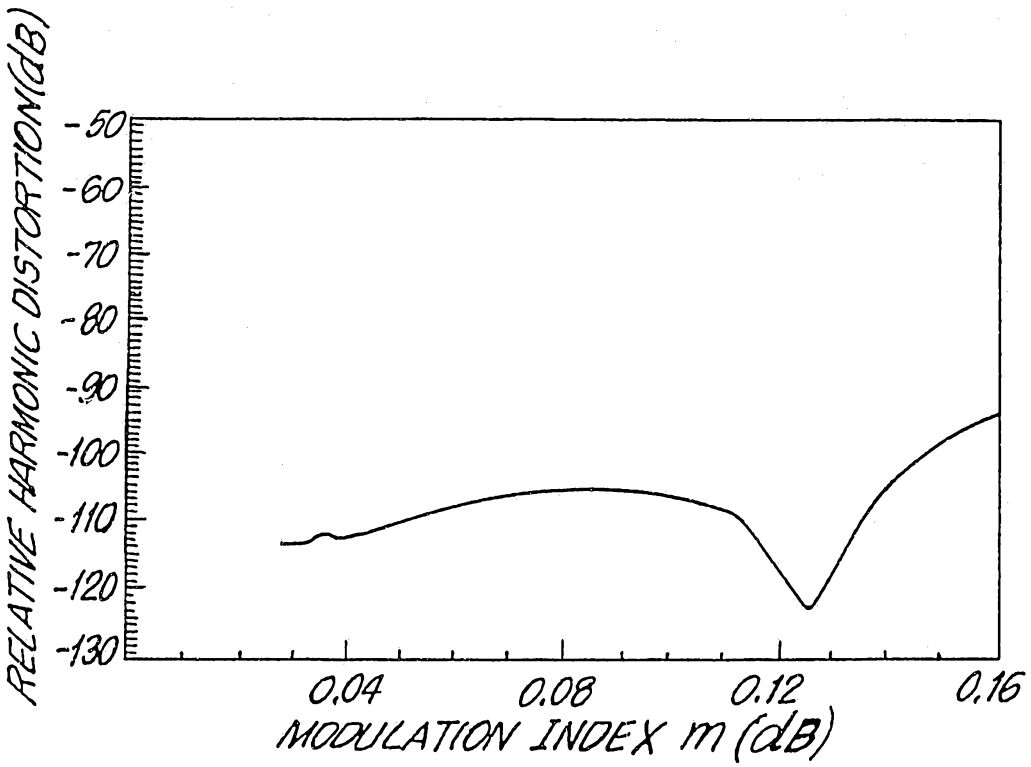
RELATIVE HARMONIC DISTORTION(dB)
-50
-60
-70
-80
-90
-100
-110
-120
-130
0.04
0.08
0.12
0.16
MODULATION INDEX m (dB)

FIG.7

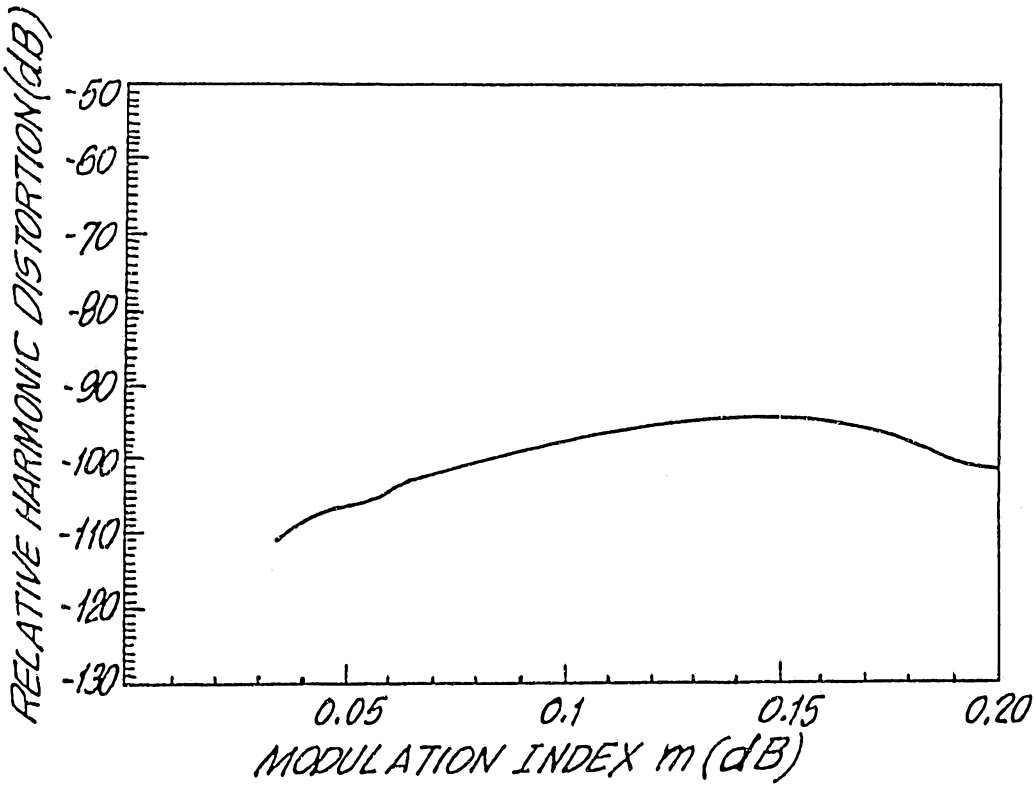
RELATIVE HARMONIC DISTORTION(dB)
-50
-60
-70
-80
-90
-100
-110
-120
-130
0.05
0.1
0.15
0.20
MODULATION INDEX m (dB)

FIG.12

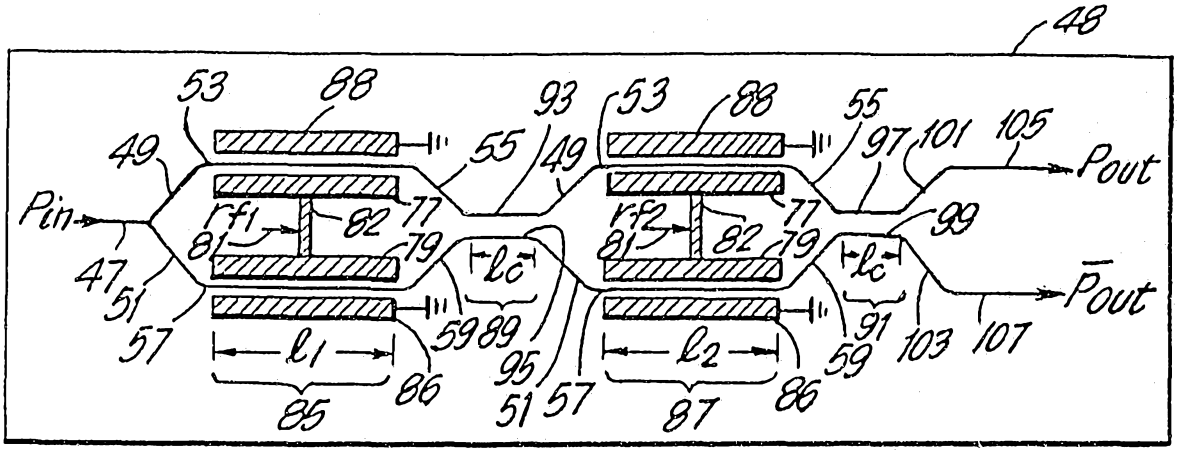
48
53
88
93
53
88
55
49
55
97
101
105
Pout
49
Pin
rf1
82
77
rf2
82
77
81
79
81
79
99
47
51
57
lc
lc
Pout
59
89
91
103
107
l1
l2
95
59
86
86
85
51
57
87

FIG.8

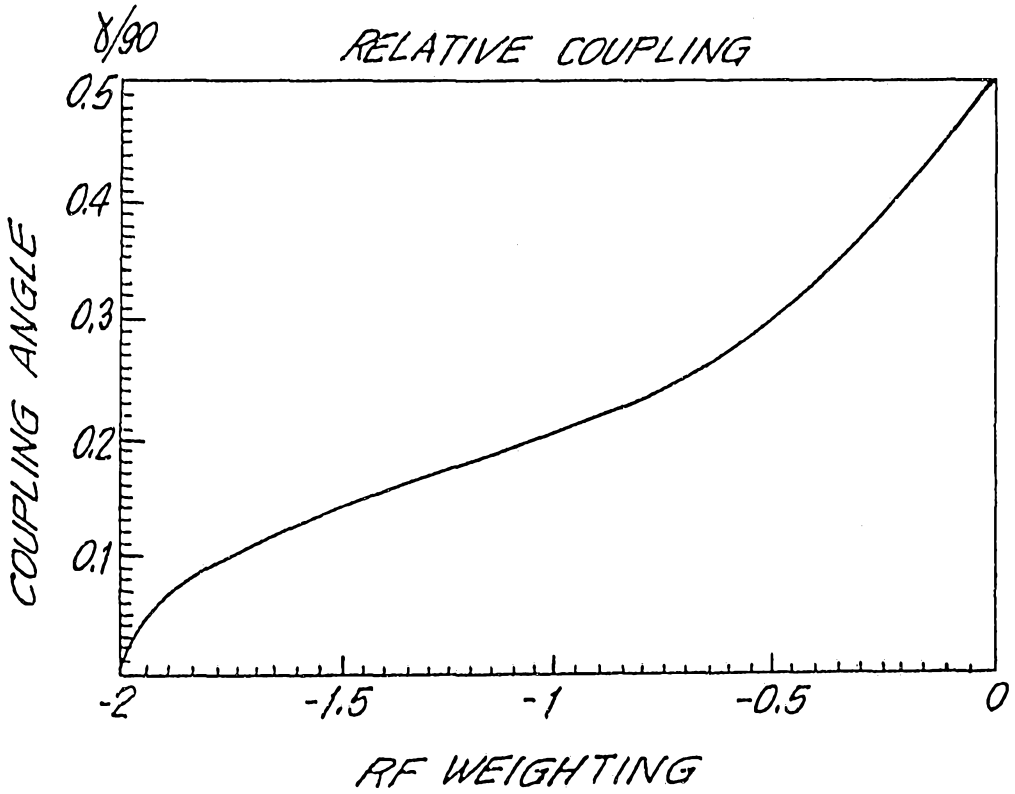
γ/90
RELATIVE COUPLING
0.5
0.4
0.3
0.2
0.1
COUPLING ANGLE
-2
-1.5
-1
-0.5
0
RF WEIGHTING

FIG.9

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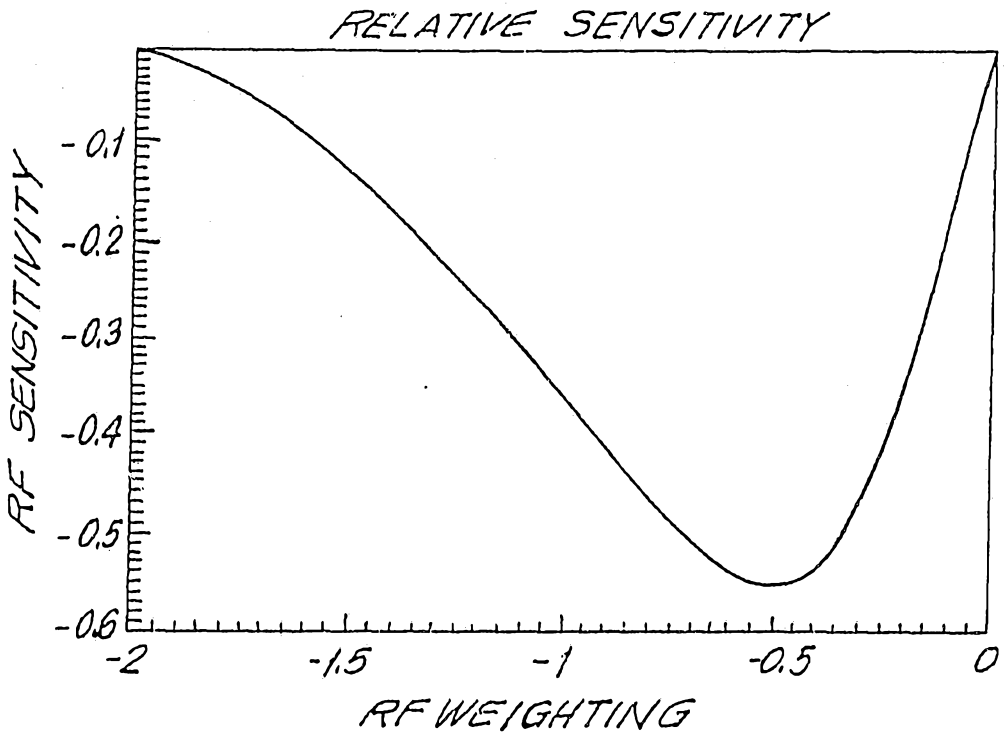

FIG. 10

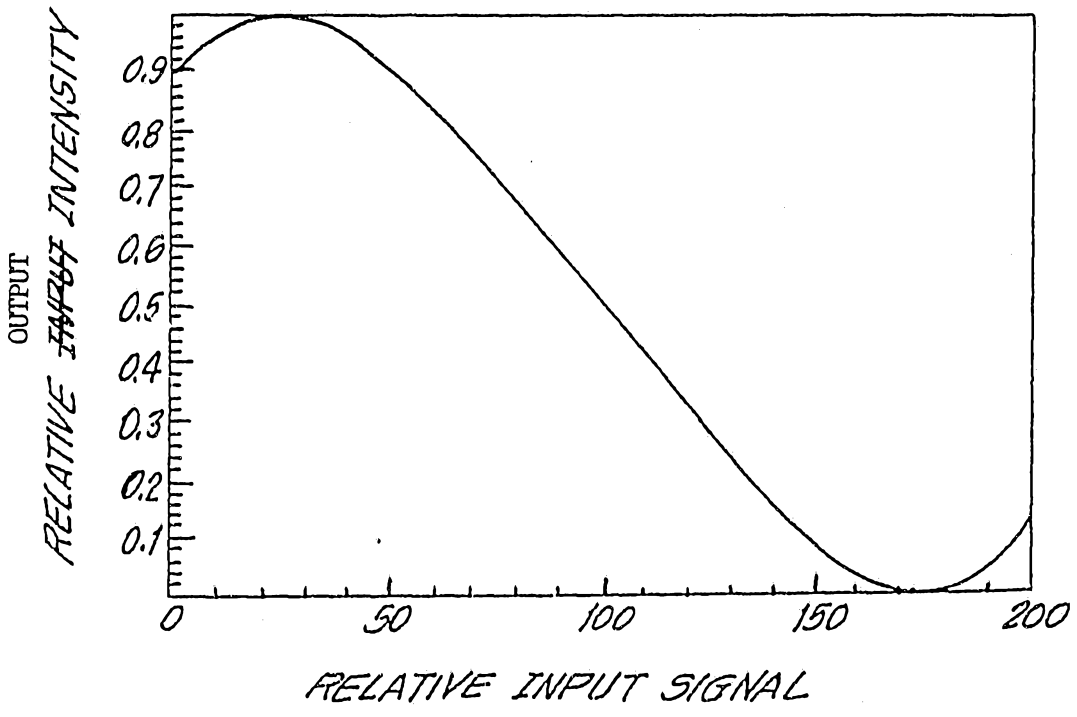

FIG. 11

AMENDED SHEET

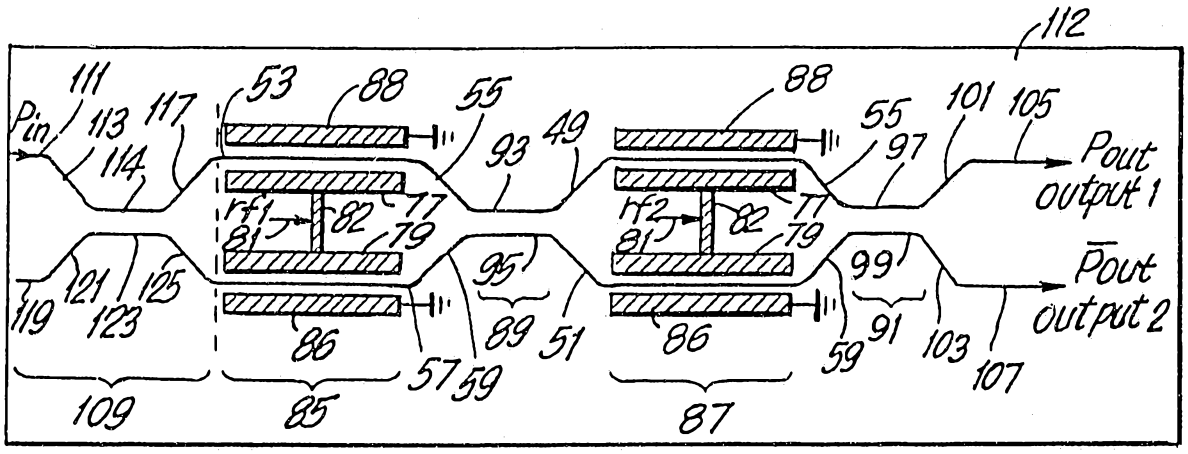
112
111
Pin
113
114
117
53
88
55
93
49
88
55
97
101
105
Pout
output 1
rf1
81
82
77
79
rf2
81
82
77
79
119
121
123
125
95
99
Pout
output 2
86
89
51
86
59
91
103
107
57
59
109
85
87

FIG.13

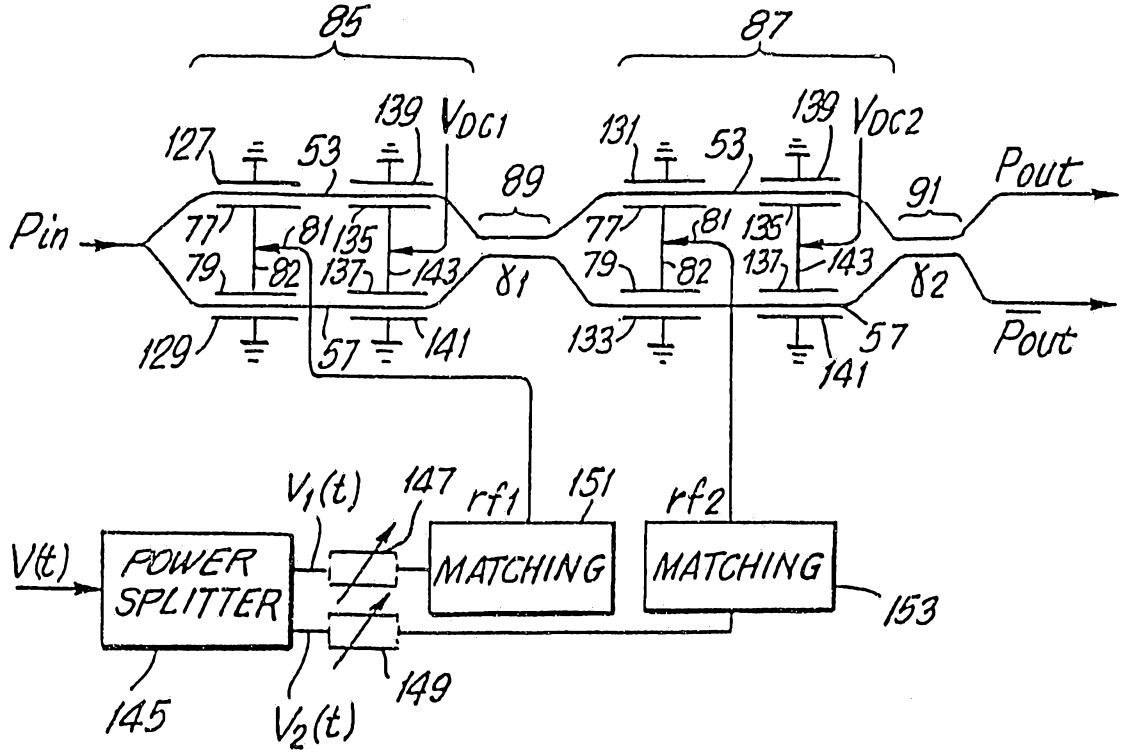
85
87
139
VDC1
139
VDC2
127
53
131
53
89
91
Pout
Pin
77
79
81
82
135
137
143
81
77
79
81
82
135
137
143
82
129
57
141
133
57
141
Pout
V1(t)
147
rf1
151
rf2
V(t)
POWER
SPLITTER
MATCHING
MATCHING
153
145
V2(t)
149

FIG. 14

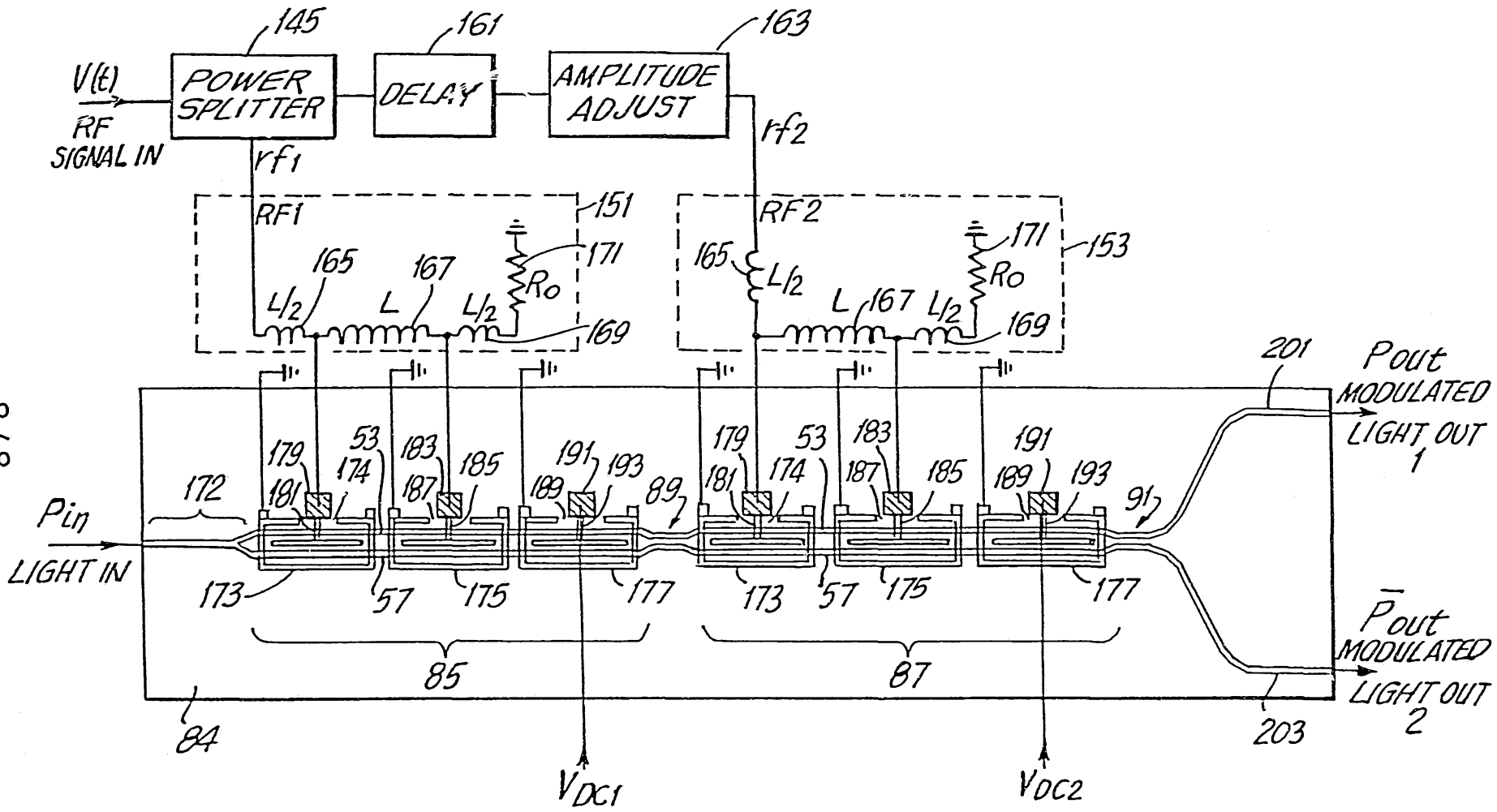
145
161
163
V(t)
RF
SIGNAL IN
POWER SPLITTER
DELAY
AMPLITUDE ADJUST
rf1
rf2
RF1
RF2
151
153
165
167
171
169
L/2
L
Ro
201
Pout
MODULATED
LIGHT OUT
1
Pin
LIGHT IN
172
179
181
53
174
183
187
185
189
191
193
89
91
173
57
175
177
85
87
84
203
P̄out
MODULATED
LIGHT OUT
2
VDC1
VDC2

FIG. 15

INTERNATIONAL SEARCH REPORT

International Application No PCT/US 93/03806

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 G02F1/313; G02F1/035

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G02F

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category[10]	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	PROCEEDING OF THE SPIE, VOL. 1583 - INTEGRATED OPTICAL CIRCUITS - September 1991, BELLINGHAM, WA, US pages 153 - 164 , XP000351959 H. SKEIE ET AL. 'Linearization of Electro-Optic Modulators by a Cascade Coupling of Phase Modulating Electrodes' cited in the application see abstract; sections 1,3-4; figures 4-7,11-12 ---	1-20
P,X	WO,A,9 300 755 (THOMSON-CSF) 7 January 1993 see the whole document ---	1-20
P,A	EP,A,0 516 064 (CRYSTAL TECHNOLOGY) 2 December 1992 cited in the application ---	
	-/--	

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"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
20 AUGUST 1993	10 SEP 1993
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	IASEVOLI R.

Form PCT/ISA/210 (second sheet) (January 1985)

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	IEEE PHOTONICS TECHNOLOGY LETTERS vol. 3, no. 9, September 1991, NEW YORK US pages 792 - 795 , XP000225781 M.L. FARWELL ET AL. 'An Electrooptic Intensity Modulator with Improved Linearity'	
P,A	WO,A,9 210 780 (THOMSON-CSF) 25 June 1992	
A	IEEE PHOTONICS TECHNOLOGY LETTERS vol. 3, no. 2, February 1991, NEW YORK US pages 144 - 146 , XP000203015 P.-L. LIU ET AL. 'In Search of a Linear Electrooptic Amplitude Modulator' cited in the application	

ANNEX TO THE INTERNATIONAL SEARCH REPORT
ON INTERNATIONAL PATENT APPLICATION NO. US 9303806
SA 73740

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information. 20/08/93

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO-A-9300755	07-01-93	FR-A- 2678455	31-12-92
EP-A-0516064	02-12-92	US-A- 5148503	15-09-92
WO-A-9210780	25-06-92	FR-A- 2670589	19-06-92