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Serial No.:

**PATENT APPLICATION**
Navy Case No. 75,773

# WIDEBAND FIBER-OPTIC SIGNAL PROCESSOR

## BACKGROUND OF THE INVENTION

### Field of the Invention

This invention deals generally with the transmission of electrical signals using an optical carrier and more particularly with a method of transmission of electrical signals by reducing the unmodulated optical carrier power so that amplifiers and high-power optical sources may be used to generate higher radio-frequency powers from a photodetector.

### Description of the Related Art

In the basic externally modulated optical communications link **10**, shown in **Figure 1**, an optical signal **12** generated by a continuous-wave laser source **14** is directed through an external optical modulator (EOM) **16** whose output **18** depends sinusoidally on the input radio-frequency (RF) or electrical signal **22**. Recently, laser **14** powers have reached the 20 to 100 mW level and the optical insertion loss of EOMs **16** range from 3 to 10 dB so that the output **18** from the EOMs **16** can be as high as 10 mW. If the optical fiber connecting the EOM **16** to the high-speed photodetector **24** is not too long or not too lossy, the optical power incident on the photodetector **24** is essentially 10 mW. Ten milliwatts of optical power on the photodetector **24** is likely to destroy the photodetector **24** or at least introduce large-signal distortions, which include harmonics and bandwidth reductions in the RF or electrical signal output **28**. Therefore an optical attenuator **26** must be used, which negates the usefulness of the high-power laser **14** by reducing the input optical power **12** and, thus, increasing the insertion loss.

To achieve linearity and maximum differential change in optical output per input voltage in the basic externally modulated optical communications link **10**, the EOM **16** is typically biased at the point at which the output is one-half of the maximum output signal, called "quadrature." When biased at quadrature, the EOM **16** optical output signal **18**, $P_{output}$ is given by

$$P_{output} = \frac{P_{input}}{2}\left[1 \pm \sin(kx)\right]$$

where $P_{input}$ is the input optical power, k is a constant, x is the input signal voltage, and the sign (±) depends on the slope of the quadrature point chosen. The sinusoidal function introduces nonlinear distortion in the signal unless the modulated depth is kept below about 71% which corresponds to approximately 20% reduction (1 dB compression) of the output signal modulation relative to a perfectly linear relationship. i.e., $P_{output} \propto P_{input}$. The modulation depth, M, is defined as

$$m=\frac{P_{\max}-P_{\min}}{P_{\max}+P_{\min}} \tag{2}$$

When kx is small the output signal can be approximated with

$$P_{output}=\frac{P_{input}}{2}\,[1+kx] \tag{3}$$

where the positive sign is taken without loss in generality. This equation can be rewritten as

$$P_{output}=P_{excess}+\frac{P_{\text{mod}}}{2}\,[kx_{average}+kx] \tag{4}$$

The second component of the right hand side is a sum of the signal kx which may be positive or negative and just enough of the input optical carrier **12** ($kx_{average}$) to ensure the modulation depth of this component does not exceed 100%. The first part of this equation $P_{excess}$ is called the "excess carrier" and represents the unmodulated optical power. If viewed as a separate optical component, this excess carrier increases the signal from a photodetector **24** since it acts like a coherent high-power local oscillator. However, this signal "gain" is linearly proportional to the excess carrier power, which is limited by the photodetector **24** to 1 to 10 mW. The excess optical power is detrimental in two ways. First, optical amplifiers are rendered useless since they are limited by the average output power and, therefore, cannot be used to only boost the modulated optical wave without amplifying the excess carrier. Second, and more importantly, the average optical power must be kept below ~1 mW to avoid signal reductions and distortions in the photodetector **24** and below ~ 10 mW to avoid damage to the photodetector **24**.

The electrical link loss can roughly be calculated as follows. For comparison purposes, the input electrical power is set to one-fourth of the half-wave voltage, $V\pi/4$, which yields a modulated depth, m, of 71%. The electrical input power then is

$$P_{\mu W,\,output}=\frac{(\frac{V_{\pi}}{4})^{2}}{2R_{INPUT}} \qquad (5)$$

where $R_{INPUT}$ is the load resistance. The radio frequency (RF) output power **28** from the photodetector **24** is calculated from the peak modulation current, $m \cdot I_{PD,aver}$, and is given by

$$P_{\mu W,\,output}=\frac{m^{2}I^{2}{}_{PD,\,aver}R_{LOAD}}{2} \qquad (6)$$

where $R_{LOAD}$ is the load resistance. The link loss is the ratio of the output electrical power to the input electrical power. Therefore, the fiber optic link transmission coefficient is proportional to the photodetector **24** average current squared. Also, for high-speed photodetectors **24** with average current limited to 1 mA, the minimum loss of a conventional link is approximately 37 dB (assuming that the input and output load resistances to be 50Ω and that the EOM 16 has a $V_\pi$=10 Volts). However, weak input signals do not provide 71% modulation depth, therefore the link loss is much higher for these signals than 37 dB.

In the prior art, the excess carrier, and the dc photocurrent it produces, have been ignored because the average power has been less than 1 mW. However, recently, there have been significant advances in laser output levels, high-speed modulators, optical amplifiers, and small high-speed photodetectors. Because of the small active volume, high-speed photodetectors cannot receive more than ~1 mW of optical power before nonlinearities, bandwidth reduction, or catastrophic damage occurs. As a result, high-power (~100 mW) lasers cannot be fully utilized to increase high-speed modulator sensitivity. New photodetector designs may increase the power handling capability, but, so long as the optical power available is larger than the photodetector power limit, this invention offers advantages and utility.

## SUMMARY OF THE INVENTION

The object of this invention is to reduce the unmodulated carrier power so that amplifiers and high-power laser sources can be used to generate higher radio frequency (RF) power output by the photodetector.

Another object of this invention is to provide a device for generating a higher RF power output by photodetectors that can be added to existing fiber-optic signal processing systems with minor system modifications.

In fiber-optic signal processing systems having the optical signal modulated by relatively weak electrical signals, high optical power levels are desired because the signal power carried by the optical carrier is proportional to the optical power. However, weakly modulated optical waves leave significant unmodulated power in the original carrier. This invention provides an apparatus for reducing the unmodulated carrier power of an optical signal processor so that amplifiers can be used to provide higher power levels in the output RF signal from a photodetector. Other optical and optoelectronic devices that exhibit optical power limits (including optical amplifiers, themselves) will benefit or exhibit increased utility as a result of reduced optical carrier power.

To maximize the signal power carried by the modulated optical carrier, the input optical power to an external modulator is maximized. In this invention a narrowband optical filter, tuned to match the filtering resonance with the optical carrier wavelength, is used causing the average optical carrier to be reduced, but not the modulation sidebands, thereby causing the modulation depth to increase. Therefore, the concurrent increase in detector signal level is accomplished without adding noise to the signal.

## BRIEF DESCRIPTION OF THE DRAWINGS

**Figure 1** shows the basic externally modulated optical communications link described in the prior art.

**Figure 2** shows the preferred embodiment of the invention utilizing a narrowband filter instead of an optical attenuator used in the prior art.

**Figure 3a** shows the plot of a typical resonator transmission, $T(\omega')$, versus normalized optical frequency for a fiber optic ring resonator (FORR).

**Figure 3b** shows the plot of a typical resonator reflection, $R(\omega')$, versus normalized optical frequency for a fiber optic ring resonator.

**Figure 4** shows the experimental model of an optical signal processor utilizing a Fabry-Perot filter.

**Figure 5** shows a plot of the reference frequency response of the fiber-optic link from the electrical input to electrical output of the experimental model of an optical processor utilizing a filter.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

This invention is an improvement upon the fiber optic signal processors of the prior art.

In the preferred embodiment of this invention, **Figure 2**, the basic externally modulated optical communications link **30** has a narrowband filter **32**, separate from the laser **38**, inserted between the external optical modulator (EOM) **34** and the photodetector **36**. The narrowband filter **32** may be of any type well known to the art, but preferably a Fabry-Perot (FP) filter having finesse, $\mathcal{F}$, in the 30-250 range with filter bandwidths extending from ~50 MHz to 400 GHz and a free spectral range (FSR) ranging from 10 GHz to 12,500 GHz. Finesse, $\mathcal{F}$, being FSR/BW and a measure of the spectral resolving power of the FP filter. A FP filter having a finesse of as high as 150 is used as a passband filter in the transmission mode and a notch filter in the reflection mode. In the FP filter **32**, the "reflected" signal is the signal of interest and is accessed by, preferably, an optical circulator (not shown) prior to the filter **32** and then forwarded to the rest of the fiber-optic link. A fiber-optic coupler (Not shown) may also function to extract the reflected signal from the FP filter **32**.

A second preferred narrowband filter **32** is the fiber optic ring resonator (FORR) filter which operates as a notch filter in an equivalent "reflection" mode. The highest currently known finesse of a passive fiber ring resonator is 1260. In a FORR filter, the "reflected" signal is the signal of interest as it contains the optical sidebands and a substantially reduced optical carrier. The "transmitted" output signal would be the optical carrier extracted from the modulated optical signal. Also, a FORR filter may include a gain element to improve the finesse.

Utilizing a continuous wave laser source **38** capable of generating an optical carrier exhibiting a linewidth that is narrow compared to the filter **32** bandwidth, the filter is tuned, or frequency locked to the laser source **38**, by matching the filtering resonance with the optical carrier wavelength by any technique currently known to the art. A typical method of frequency locking the optical carrier and the filter **32** is described in Day et al., <u>30 Hz-Linewidth, Diode-Laser-Pumped,</u>

Nd:GGG Nonplanar Ring Oscillators by Active Frequency Stabilization, Electronics Letters, Vol 25, No. 13, pp 810-812, Jun 89. The optical carrier would then have an integer number for the normalized frequency and the sidebands would have a normalized frequency ~ 0,02 to ),50 away from the carrier (depending on filter finesse and performance desired). As shown in **Figures 3a** and **3b**, the optical carrier is them transmitted and the sidebands are reflected. The resonator transmission, $T(\omega')$, **Figure 3a**, and reflection, $R(\omega')$, **Figure 3b**, versus normalized optical frequency $\omega = \omega \cdot nL/2\pi c$ is derived in Stokes et al., All-single-mode Fiber Resonator, Optics Letters Vol. 7, No. 1, pp 288-290, Jan 82. With a high finesse ($\mathcal{F}$) and a narrow-linewidth optical carrier, the frequency of operation extends from the filter half-bandwidth (~100 MHz) to the next resonance of the filter (>20 GHz). Other modulator **34** and filter **32** combinations are possible, e.g., a Mach-Zehnder filter may be used in conjunction with a phase modulator.

In an experimental model, **Figure 4**, the output of the laser source **52** (a 1.3 micron Nd:YAG laser Model 120, manufactured by Lightwave Electronics of Mountain View, CA) is coupled into a polarization maintaining single mode optical fiber **54** feeding an external optical modulator (EOM) **56** (i.e., a lithium niobate modulator with 18 GHz bandwidth manufactured by United Technologies of Bloomfield, CT). The modulated optical signal from the EOM **56** is directed to input port **58a** of a fiber-optic 50/50 splitter **58** (3 dB directional coupler); preferably the 50/50 splitter **58** would be replaced by an optical circulator. The optical signal entering the splitter **58** is split into two output signals. The first output signal is applied through port **58b** to a filter **62** (used in reflection mode). The filter utilized in the experimental installation was a Fixed Fiber Fabry-Perot Filter, Model FFP-100, manufactured by Micron Optics, Inc. of Atlanta, GA, with a free spectral range of 75 GHz and a bandwidth at 1.3 microns of ~360 MHz, yielding a finesse of over 200. The second output signal is applied through port **58c** to a mirror **64** providing a reference optical signal. The reflected optical signal from the filter **62** and the mirror **64** reenter the splitter **58** through ports **58b** and **58c**, respectively, and 50% of each reflected signal is directed through output port **58d** to a photodetector **66**. Two On/Off switches **66** and **68** are inserted in the filter and mirror circuits, respectively, and are made of lengths of optical fiber that, for the Off condition, are tightly wound around small mandrels (not shown) -- the bend loss of the fiber results in complete extinction of the optical signal.

The experiment consisted of first switching Off the signal reflected from the filter **62** by the use of switch **66** and measuring the reference frequency response of the fiber-optic link from the electrical input **72** to electrical output **74**, shown as Trace "A"in **Figure 5**. The reference signal is then switched Off by the use of switch **68** and switch **66** is placed in the On position to allow the reflected signal from the filter **62** to enter the splitter **58**. The optical light from the laser source **52** (the optical carrier) is tuned to a filter **62** resonance for maximum transmission and minimal reflection. If there is no noticeable relative drift between the filter **62** resonance and the wavelength of the optical light from the laser source **52**, frequency locking is not required. The optical power of the light from the laser source **52** is then adjusted to yield a photodetector **66** average current equal to the photodetector **66** average current used in the reference measurement. The carrier response is then measured and is shown as Trace "B" in **Figure 5**. Shown in **Figure 5** is over a 9 dB improvement in electrical output signal over the reference measurement represented by trace "A". In the experimental installation, the signal enhancement is limited to 9 dB because of the residual carrier reflections from the filter **62**. Improved filters or multiple filters, can increase the signal enhancement to greater than 20 dB. It is noted that in this experiment the 9 dB gain was exhibited over the full bandwidth from about 500 MHz to 25 GHz.

The foregoing apparatus provides a unique and novel way to reduce the loss in fiber-optic signal processing and communications systems. In this invention the user is allowed great freedom in the choice of components but is required to assure optical locking between the laser and filter. By an appropriate choice of a filter **62**, modulation can be carried out at any input frequency range with a corresponding reduction in link loss without introducing any additional noise, amplitude ripple, or phase distortion such as that found when microwave amplifiers are used to increase the microwave signal **74**. Unlike microwave amplifiers, this apparatus offers a very broadband amplification representing a substantial cost and power saving in the overall link. With this apparatus, and the same photodetector current as a conventional link, greater microwave power is generated by the photodetector, hence, greater radio frequency output powers are obtained when a saturating optical beam is applied to the photodetector. Even if the modulation depth of an optical source is large (~100%), in some applications, a continuous wave optical signal (or optical carrier) is added to the well-modulated optical carrier as part of the signal processing. This apparatus allows removal of the excess carrier, if desired for additional signal processing, even when the excess carrier is not origionally due to poor modulation depth. Further, in this apparatus the incoming modulation can be phase modulated and, with an appropriate filter (i.e., Mach-Zehnder), simultaneously convert the phase to amplitude modulation as well as filters the optical carrier resulting in an increase to the modulation depth.

Although the invention has been described in relation to exemplary preferred embodiments thereof, it will be understood by those skilled in this art that still other variations and modifications can be affected in these preferred embodiments without detracting from the scope and spirit of the invention.

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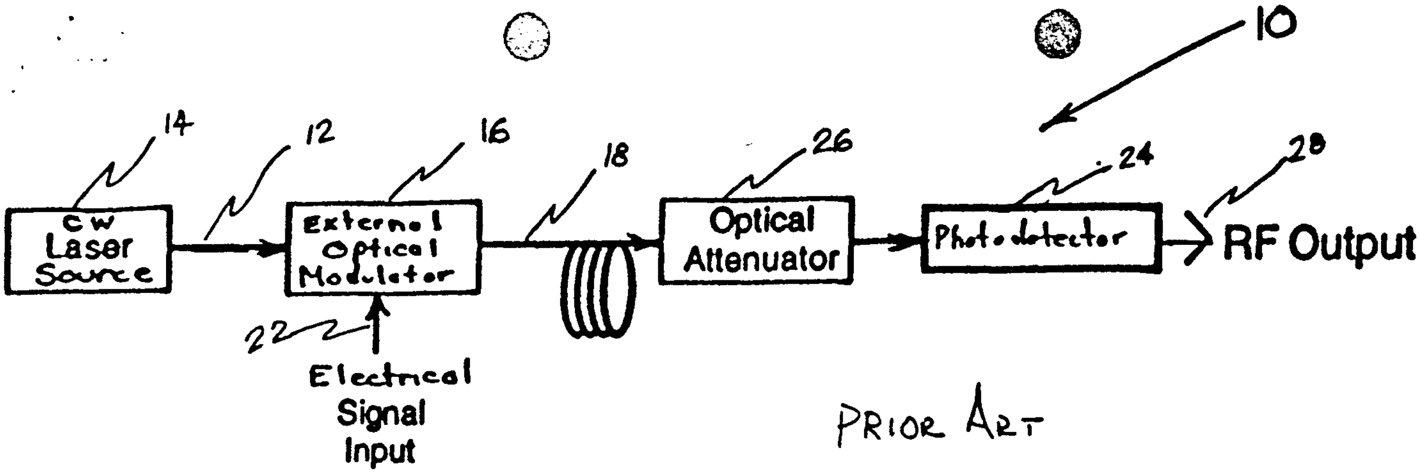
## ABSTRACT

In the transmission of electrical signals using an optical carrier the signal power carried by an optical carrier is proportional to the optical power. High optical power levels are desired for optical carriers that are modulated by weak electrical signals, however, significant unmodulated power is left in the original carrier after processing. To maximize the radio frequency (RF) signal power generated by a given (maximized) photodetector current (for a given input power), in this invention, the optical carrier power is reduced. This is accomplished by the addition of a narrowband optical filter, such as a Fabry-Perot filter, to reduce the average optical carrier power without reducing the modulation sidebands, which results in an increased modulation depth. Therefore, greater RF and microwave power is generated by a photodetector with the same photocurrent. With a laser source exhibiting a beam whose linewidth is narrow compared to the filter bandwidth, the filter is tuned, or frequency locked, to match the filtering resonance with the optical carrier wavelength. With the high finesse filter and narrow-linewidth laser beam, the frequency range of operation is extended from the filter half-bandwidth to the next resonance of the filter. Thus, broadband effective gain results without introducing additional noise.



PRIOR ART

FIG. 1

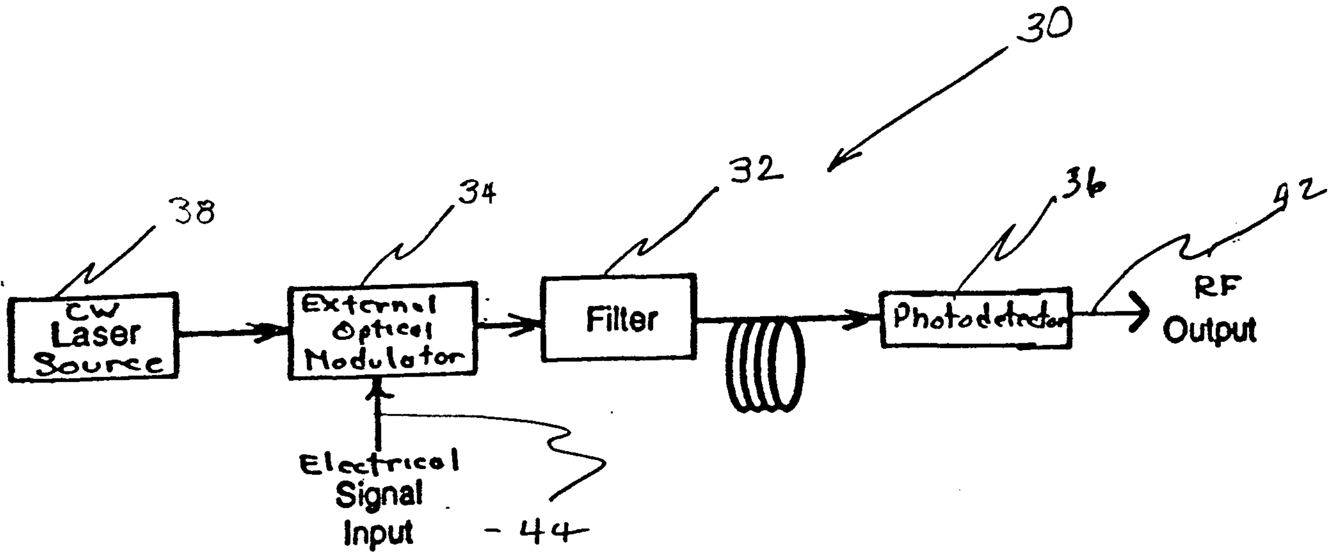
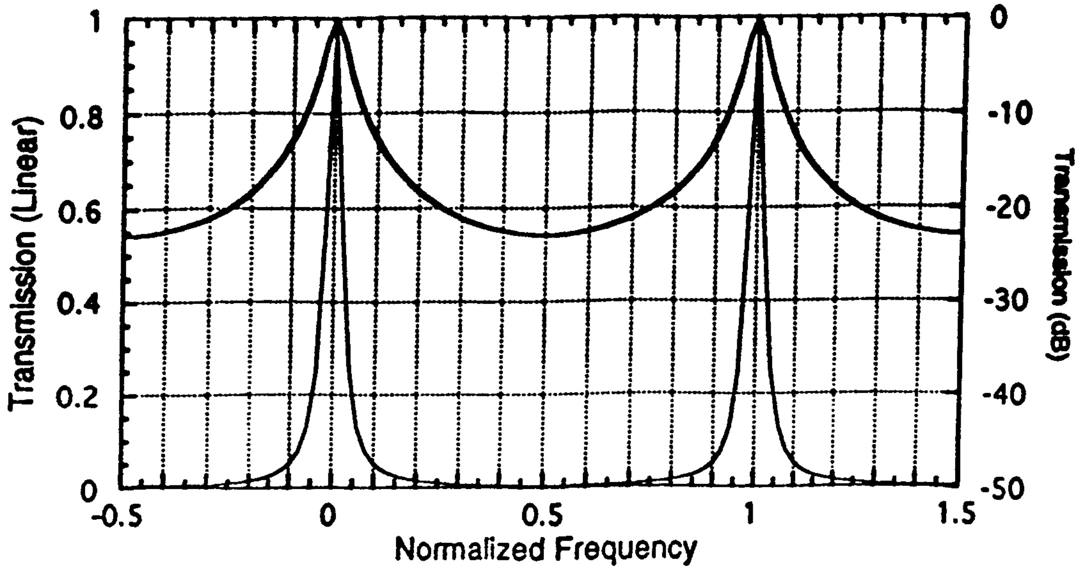
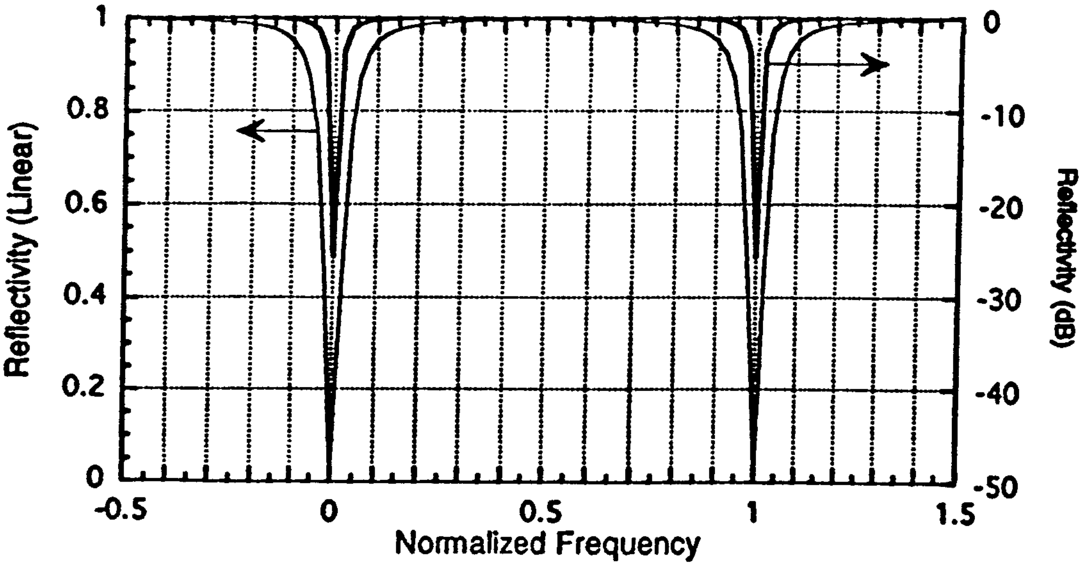


FIG. 2



Transmission (Linear)
1
0.8
0.6
0.4
0.2
0
-0.5
0
0.5
1
1.5
Normalized Frequency
0
-10
-20
-30
-40
-50
Transmission (dB)

Fig. 3a



Reflectivity (Linear)
1
0.8
0.6
0.4
0.2
0
-0.5
0
0.5
1
1.5
Normalized Frequency
0
-10
-20
-30
-40
-50
Reflectivity (dB)

Fig. 3b

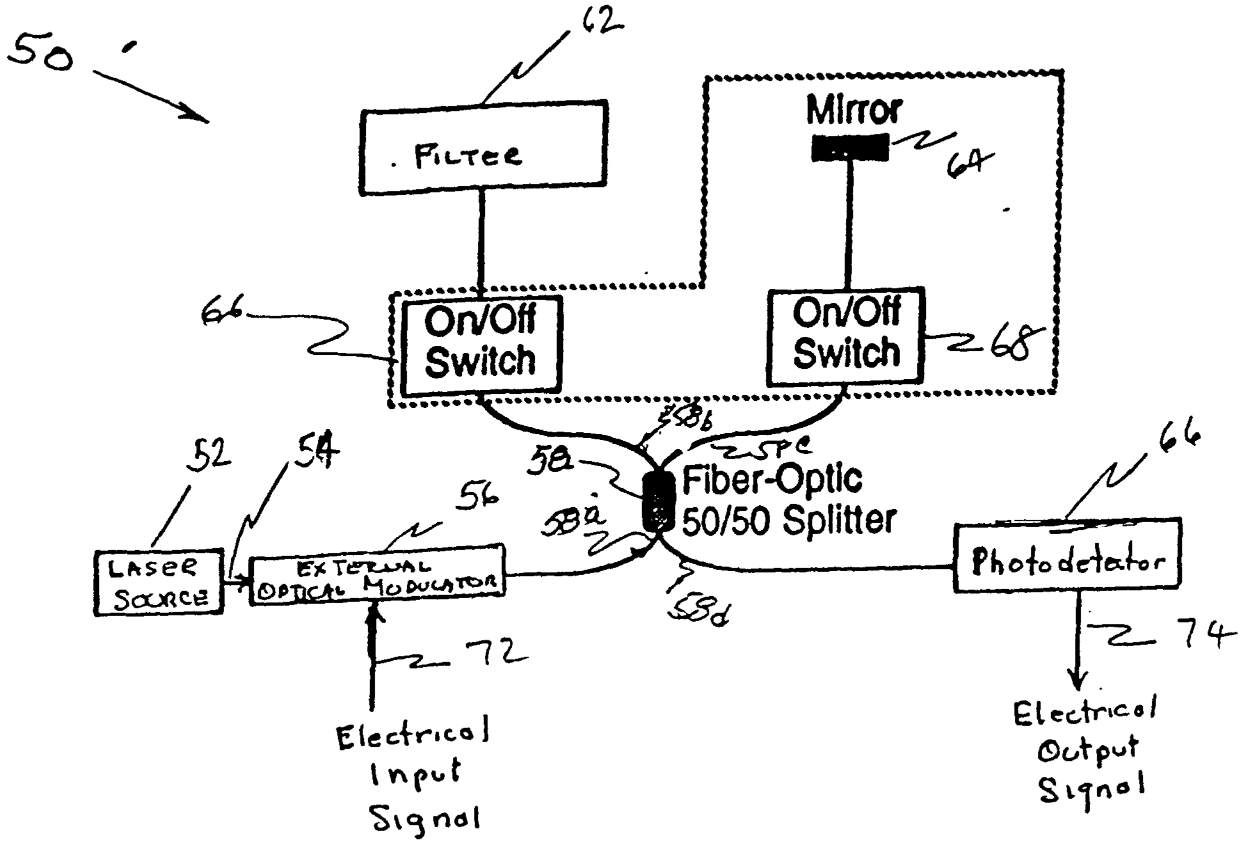

50
62
Filter
Mirror
64
66
On/Off Switch
On/Off Switch
68
58b
58c
52
54
58a
Fiber-Optic 50/50 Splitter
66
56
58a
Laser Source
External Optical Modulator
Photodetector
58d
72
74
Electrical Input Signal
Electrical Output Signal

Fig. 4

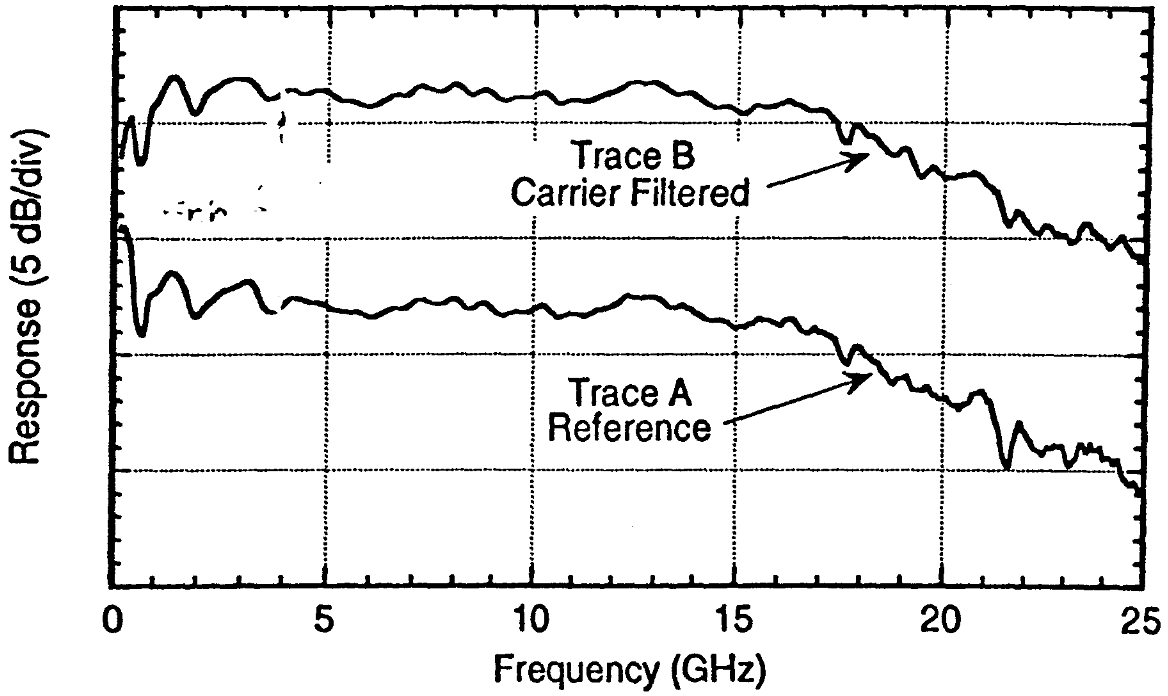

Response (5 dB/div)
Trace B Carrier Filtered
Trace A Reference
0
5
10
15
20
25
Frequency (GHz)

Fig. 5