Serial No.: 09/620,324

Filing Date: 17 JULY 2000

Inventor: ALLAN WARD

NOTICE

The above identified patent application is available for licensing. Requests for information should be addressed to:

ASSOCIATE COUNSEL (PATENTS)
CODE 1008.2
NAVAL RESEARCH LABORATORY
WASHINGTON DC 20375

PATENT APPLICATION/TECHNICAL DIGEST PUBLICATION RELEASE REQUEST

FROM: Associate Counsel (Patents) (1008.2)
TO: Associate Counsel (Patents) (1008.2)

Via: (1) Keith Williams (Code 5652)
(2) Division Superintendent (Code 5600)
(3) Head, Classification Management & Control (Code 1221)

SUBJ: Patent Application/Technical Digest entitled: **"IMAGE REJECTING MICROWAVE PHOTONIC DOWNCONVERTER"** Request for release for publication.

REF: (a) NRL Instruction 5510.40C
(b) Chapter 6, ONRINST 5870.1C

ENCL: (1) Copy of Patent Application/Technical Digest

1. In accordance with the provision of references (a) and (b), it is hereby requested that the subject Patent Application/Technical Digest be released for publication.

2. It is intended to offer this Patent Application/Technical Digest to the National Technical Information Service, for publication.

3. This request is in connection with Navy Case No. 79,800

7/21/00
(date)

BARRY A. EDELBERG
Associate Counsel (Patents)

FIRST ENDORSEMENT

Date: 26-July-2000

FROM: Keith Williams (Code 5652)
TO: Division Superintendent (Code 5600)

1. It is the opinion of the Inventor(s) that the subject Patent Application/Technical Digest (is) (is not) classified and there is no objection to public release.

Inventor's Signature

SECOND ENDORSEMENT Date: 27 July 2000

FROM: Division Superintendent (Code 5600)
TO: Classification Management & Control (Code 1221)

1. Release of Patent Application/Technical Digest (is) (is not) approved.

2. To the best knowledge of this Division, the subject matter of this Patent Application/Technical Digest (has) (has not) been classified.

3. This recommendation takes into account military security, sponsor requirements and other administration considerations and there in no objection to public release.

Dr. Craig Hoffman, Acting Superintendent
Optical Sciences Division, Code 5600

Division Superintendent

THIRD ENDORSEMENT Date:

FROM: Head, Classification & Control (Code 1221)
TO: Associate Counsel (Patents) (1008.2)

1. This Patent Application/Technical Digest is authorized for public release.

Head, Classification, Management & Control

Inventors: Ward et al.
Serial No.

PATENT APPLICATION
Navy Case No. 79,800

IMAGE REJECTING MICROWAVE PHOTONIC DOWNCONVERTER

BACKGROUND OF THE INVENTION

Field of the Invention

This invention pertains generally to a device for shifting microwave signals in the direct current (DC) to 20 GHz range to an arbitrary intermediate frequency between DC and 20 GHz without interference between the original and converted signals, and more specifically to a device that prevents the image-sideband associated with the intended frequency side-band to be converted to an intermediate frequency band between DC and 20 GHz.

Description of the Related Art

There are generally two types of conventional microwave components that may provide significant frequency translation with image rejection; the digital phase modulator and the electronic image rejection mixer. In the case of the digital phase modulator, a Serrodyne phase modulated waveform is applied to the desired electrical signal to be shifted. **SEE**, Cumming, THE SERRODYNE FREQUENCY TRANSLATION, Proc. of the IRE, Vol. 45, pg. 175, 1957. The achievable image rejection is limited by the number of discrete electrical signals that can be implemented in hardware, usually less than ten. This limits the achievable rejection to below 25 dB. In the case of an electronic image rejection mixer, an oscillator is used to shift the original frequency. The achievable image rejection is limited by the ability to create, from the incoming broadband microwave signal, two broadband microwave signals exactly 90 degrees out of phase with exactly the same amplitude, independent of the incoming frequency. Typical devices with 3-degree phase error and a 0.25 dB amplitude imbalance are limited in their image and carrier rejection to less than approximately 30 dB.

The electrical frequency in the existing prior art can usually operate only over a narrow bandwidth due to engineering complexities. In the mixer example, it becomes very difficult to phase and amplitude match over a broad bandwidth, therefore commercial devices are usually limited to instantaneous bandwidths of less than 1 - 2 octaves at microwave frequencies. In the phase shifter example, the tradeoff between creating many bits for good rejection is not compatible with broadband operation because of the many paths the signal takes; therefore commercial devices are usually limited to instantaneous bandwidths of less than 12 GHz. Currently the state of the art in optical modulator bandwidth is above 75 GHz, which is significantly above commercially available electrical mixer or phase shifter products.

BRIEF SUMMARY OF THE INVENTION

The object of the invention is to provide a device for up-converting broadband electrical signals, filtering-out image frequencies in the electrical domain and then down-converting the desired frequency using optical techniques.

Another object of this invention is to obtain a frequency shifted microwave signal utilizing electro-optic modulators and band-pass electronic filters.

Another objective of this invention is to provide an analog device that does not rely upon phase or amplitude matching to achieve image rejection.

These and other objects of the invention are accomplished by an image rejecting microwave photonic downconverter using a microwave sub-carrier modulation technique without concern for image frequency interference in the shifted signal, thereby allowing telecommunications systems to downconvert densely multiplexed communications channels into a low frequency band where conventional electronics can perform signal-processing functions. Further, with the image rejecting microwave photonic downconverter, incoming microwave signals can be processed without ambiguity in direction finding applications, allowing remotable, multioctave microwave signal processing for frequency and phase determination. A plurality of lasers, a first laser providing an optical carrier that is modulated by a first electro-optic modulator with a sinusoidal electrical signal generated by a first local oscillator (LO) and a second laser providing an optical carrier that is modulated by a second electro-optic modulator with a sinusoidal electrical signal generated by the second local oscillator; are transmitted independently through two polarization-maintaining (PM) optical fibers of arbitrary length to a distant point. At the distant point, the first modulated optical signal is converted to the electrical domain using a photodetector and mixed with an input from an ultra-broadband radio frequency (RF) antenna receive-array, shifting the entire RF band to a higher frequency band equal to the original RF plus the LO frequency. This upshifted frequency band is amplified and passed through a band-pass filter to attenuate frequencies outside the up-converted pass-band. The filtered signal is electro-optically mixed with the modulated optical signal from the second local oscillator using a 3rd modulator and the resulting intermediate frequency (IF)-modulated optical signal is detected using a second photodetector and transmitted to an electrical output port of the system.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a block diagram of an image rejecting optical downconverter.

Figure 2a shows the mixing that occurs between the radio frequency signal and the injected signal from the first local oscillator.

Figure 2b shows the superposition of desired and undesired components within the IF output band.

Figure 2c shows that by using a two-step frequency shift, the original radio frequency band is upconverted using the first local oscillator signal so that only the desired portion of the band passes through a bandpass filter.

Figure 2d shows the filtered output of the upconverted RF upon leaving the bandpass filter downconverted to the desired IF frequency range using a fixed second local oscillator carrier.

Figure 3 shows both a desired signal and an image at the output of the system when the bandpass filter is removed.

Figure 4 shows a greatly attenuated image when the bandpass filter is inserted.

DETAILED DESCRIPTION OF THE INVENTION

In the preferred embodiment of the image rejecting microwave photonic downconverter **10**, as shown in **Figure 1**, a first laser **12,** L1, provides an optical carrier **13** at a wavelength λ_1 which is modulated by a sinusoidal electrical signal **14** generated by a local oscillator **16**, LO1, in a first optical modulator **18**, MZM1, such as a Mach-Zehnder optical modulator, to produce a first modulated optical carrier **22** which is applied to a first high speed photdetector **24**, PD1, where the optical carrier **22** is converted to an electrical signal **26**, which in turn is amplified by a first amplifier **28**, A1 and drives an upconverting mixer **34**. The modulated optical carrier **22** is carried from MZM1 **18** to PD1 **24** by a polarization-maintaining (PM) optical fiber. In the electronic mixer **34**, M1, the amplified signal **32** is mixed with an analog ultra-broadband radio frequency (RF) signal **36** from a remote antenna receive-array (not shown)to produce a up-shifted frequency band signal **38**. The mixer **34** acts to shift the entire RF band to a higher frequency band equal to the original RF frequency plus the frequency of LO1. This up-shifted frequency band signal **38** is amplified in a second amplifier **42**, A2, and applied to an electronic band pass filter **44**, BPF, which attenuates frequencies outside the up-converted pass-band.

A second laser **48**, L2, centered at wavelength λ_2 provides a second optical carrier **49** which is modulated by a sinusoidal electrical signal **54**, generated by a second local oscillator **56,** LO2, in a second optical modulator **52**, MZM2, also a Mach-Zehnder optical modulator, to produce a second electro-optically modulated carrier **58**.

The filtered up-shifted frequency band signal **46** from the band pass filter **44** is electro-optically mixed in a third optical modulator **62**, MZM3, with the optically-carried signal **58** from LO2 **56**, which shifts (downconverts) the filtered up-shifted frequency band signal **46** to a lower intermediate frequency (IF) signal **64**.. This IF band signal **64** is detected by using a second photodetector **66**, PD2, and transmitted to the electrical outport of the system for application to user electronics **68**.

The lasers **12** and **48** are of a relatively low intensity level and, preferably, are shot noise limited. A semiconductor distributed-feedback (DFB) laser has been found to be adequate for the system, however any laser meeting the requirements may be used. Also, a single mode laser is preferred, however a multimode laser may be utilized. The only restriction is that the laser be low noise.

The optical fibers connecting MZM1 **18** with PD1 **24** and MZM **62** with PD2 **66** are single mode fibers, however, prior to the modulators **18**, **52**, and **62**, the optical fiber is a polarization preserving optical fiber because MZM1 **18**, MZM2 **52** and MZM 3 **62** are polarization sensitive.

The first and second modulated optical carriers **22** and **58**, respectively, may be transmitted independently by two polarization-maintaining (PM) optical fibers of arbitrary length because the local oscillators **16** and **56** are at different frequencies. In the case of thermal fluctuations, or other irregularities, the phase does not have to be kept constant between the outputs **22** and **58** of the modulators **18** and **52** because of the lack of any phase relationship between the two local oscillators LO1 **16** and LO2 **56**

LO1 **16** and LO2 **56** have low phase noise characteristics. In this application, any local oscillator of decent quality may be used, such as a cavity oscillator. However, it is noted that LO1 **16** is tunable and acts to translate a desired portion of the received RF frequency band through the bandpass filter. LO2 **56** need not be tunable. The purpose of LO1 **16** being tunable is that it shifts the RF input frequency **36** into the pass band of the bandpass filter **44**. The LO1 **16** frequency is determined by the RF input signal **36** frequency range, DC to 18 GHz, at the input, and on the frequency range of the bandpass filter **44**. In order to avoid overlap between the original RF input band **36** and the filter passband **44** at the output of the electronic mixer **34** (similar to the unisolated RF indicated in **Figure 2b**), the filter **44** is chosen so that the lower limit of the filter passband is a few GHz higher than the maximum RF input **36** frequency. In addition, LO isolation becomes a concern as the minimum RF input **36** frequency approaches DC because the LO frequency required to upconvert will approach the lower limit of the filter passband. As the RF input frequency of interest **36** increases from low frequencies to high frequencies, the frequency of LO1 **16** is decreased from its maximum by the same amount so that the corresponding upconverted frequency **38** lies within the filter passband **44**. The frequency of LO2 **56** is constant because the desired portion of the upconverted mixer output **38** is always within the fixed filter passband.

LO1 **16**, as previously stated, is tunable and acts to translate, in the frequency domain, a desired portion of the received RF frequency band **36** through the bandpass filter **44**. In this way, different regions of the RF band **36** can be transmitted through the filter **44** and down-converted to the IF band **67**. Because of the excellent RF to IF isolation of the system **10** due to a 50 to 80 dB filter **44** rejection, the IF band **67** can exist in any frequency range, as long as the maximum frequency of the IF band **67** is less than the LO2 **56** frequency. The width of the IF band **46** is determined by the width of the bandpass filter **44**. Image and fundamental carrier rejection is achieved because those frequency bands are attenuated by the band-pass filter **44**, and therefore are not down-converted to the IF band **67**.

The only specific requirement for the photodetectors PD1 **24** and PD2 **66** is that they have enough bandwidth to cover the IF frequency range of the device.

The mixer **34** is a triple balance mixer so as to provide ultra-wideband capability; it must have a large bandwidth signal capability at the input and convert the RF signal **36** to a broadband signal at the output **38** so as to provide a signal that is easily processed by the present day electronics. This requirement is well known to those skilled in the art for a receive system. However, the mixer may be of any type well known to those skilled in the art as long as it covers the input frequency range desired. Therefore, if you only want to look at a few GHz, then a double-balanced or a single-balanced mixer may be used.

The amplifiers, A1 **28** and A2 **42**, are typically an ultrawideband and a narrowband amplifier, respectively. The first amplifier A1 **28** must cover the range of possible LO1 **16** frequencies. The second amplifier, A2, **42** has to be at least as wide as the filter bandpass **44**. Therefore, the amplifier must typically be wider to assure that the original Rf frequency passes through the bandpass filter **44**.

Typically the bandpass filter **44** is a cavity filter with good rejection through the RF frequency range, low loss within the bandpass frequency range and an attenuation of from 60 to 70 dB.. Therefore, a typical cavity filter with a DC to 18 GHz range is suitable for the bandpass filter **44**.

Figures 2a through **2d** depict a graphical representation of the traditional and image rejecting downconverter input signals. **Figure 2a** shows the mixing that occurs between the radio frequency signal and the injected signal from the first local oscillator. **Figure 2b** shows the superposition of the resulting mixer IF output. **Figure 2c** shows that by using a two-step frequency shift, the original radio frequency band is upconverted using the first local oscillator signal so that the desired portion of the band passes through a bandpass filter. **Figure 2d** shows the filtered output of the upconverted RF upon leaving the bandpass filter downconverted to the desired IF frequency range using a fixed second local oscillator carrier. It should be noted that, while each of **Figures 2a** through **2d** depicts either an upconversion or downconversion for simplicity, the fact is that both upconversion and downconversion occur in each mixing process. However, only one of these processes will be relevant in each case due to the selectivity of the filter or RF receiver. **Figure 3** shows both a desired signal and an image at the output of the system when the bandpass filter is removed. **Figure 4** shows a greatly attenuated image when the bandpass filter is inserted.

The information shown in **Figures 3** and **4** was obtained in an application of the image rejecting downconverter using a Hewlett Packard (HP) 8510C network analyzer system and an

HP 8563 spectum analyzer. Two tones were applied to the RF input **36** of the system using isolators and a 3-dB microwave coupler. One tone was set to a center frequency of 6000 MHz, representing the desired RF signal, and the second "undesired" tone was set to a center frequency of 2000 MHz plus a small offset of 40 MHz. Since the "undesired" image tone would be downconverted to the same output IF frequency **67,** with LO1 - LO2 set to 4000MHz, the small offset was added to distinguish between the image and the desired signal. Following the signal path through the system, the two RF tones are upconverted with LO1 **16** set to 15.3 GHz. Thus, the tone representing the lower sideband is shifted to 17.3 GHz. The passband of the filter is between 21.3 and 23.3 GHz. LO2 **56** was set to 19.3 GHz which downconverts both the 21.3 GHz tone and the 17.3 GHz tone (the image) to 2 GHz, separated by the 40 MHz offset. **Figure 3** shows that both the desired signal and the image appear at the output **67** port of the system (IF2) when the bandpass filter **44** is removed. **Figure 4** shows that the image is greatly attenuated when the filter **44** is inserted, with very little attenuation of the desired RF. This test demonstrates both image rejection and RF to IF isolation of approximately 60 dB.

The invention described herein provides image rejection of greater than 60 dB across more than 12 GHz, exceeding commercial devices by 25 to 45 dB. By virtue of low-loss optical fibers, this invention allows the lasers and local oscillators to be separated by several kilometers from the remainder of the system. Thus this system may be implemented using a remote antenna site, which is advantageous in many situations.

With traditional downconverting systems, the IF bandwidth is limited to the region outside the RF band due to RF-to-IF isolation considerations. For a 0.1 - 18 GHz system, this would allow for only a DC - 100 MHz downconverted IF band. **SEE**, Linsay et al., PHOTONIC MIXERS FOR WIDEBAND RF RECEIVER APPLICATIONS, IEEE Trans. MTT, Vol 43, No. 9, pp. 2311-2317, Sep. 1995 and Gopalakrisnan et al., IEEE Trans. MTT, Vol. 43, No. 9, pp. 2318- 2323, Sep. 1995. This invention allows the IF band to exist within the RF band, without interference, by using a two-step frequency shift technique and band-pass electronic filters.

With the microwave-photonic image rejecting downconverter, it is also possible to implement microwave sub-carrier modulation techniques without concern for image frequency interference in the shifted signal. **SEE**, Chao et al., IEEE Trans. MTT, Vol 45, No. 8, pg. 1478, 1997. This allows telecommunications and CATV systems to downconvert densely multiplexed communications channels into a low frequency band where conventional electronics can perform signal-processing functions.

Another feature is highlighted by considering the photonic link noise figure (NF). Assuming a 50-ohm, shot noise limited system, the relationship between NF, detector current, and modulator half-wave voltage, V_π, is as described in Williams et al., OPTICALLY AMPLIFIED DOWNCONVERTING LINK WITH SHOT-NOISE-LIMITED PERFORMANCE, IEEE Photonics Tech. Lett., Vol. 8, No. 1, pp. 148-150, Jan. 1996. Also **SEE**, Nichols et al., OPTIMIZING THE ULTRAWIDE-BAND PHOTONIC LINK, IEEE Trans. MTT, Vol. 45, No, 8, pp. 1348-1389, Aug. 1997. From this analysis a typical photodetector current and V_π of 4 mA and 10 V, respectively, a noise figure well above a desired maximum NF of 15 dB is predictable

Therefore, barring any advances in modulator V_π, phase matched preamplifiers are necessary at an antenna array to sufficiently decrease the noise figure of the system.

Since the invention mixes RF signals to a relatively narrow passband, the phase matching requirements normally encountered are eliminated for coherent or incoherent applications. This invention makes phased matched direction finding arrays much more practical due to the reduced sensitivity requirements of the modulators **18, 52** and **62**. In traditional phase sensitive direction finding (DF) arrays which use optical modulators at the antenna site, the use of phase and amplitude matched preamplifiers over the entire RF bandwidth is necessary to achieve low noise figures. This invention relaxes those requirements since phase and amplitude matched amplifiers are only required over the desired filter pass-band, which in turn, is only as wide as the desired IF processing bandwidth. This is a subtle, but very important, advantage of this invention.

Referring again to **Figure 1**, an electro-optic modulator (e.g., Mach-Zehnder modulator) can perform the mixing function of the conventional microwave mixer **38**, M1. Also, the two modulated optical carriers **22** and **58** may be combined onto a single PM optical fiber (assuming the optical carriers are of different wavelengths) using wavelength division multiplexing (WDM) techniques well known to those skilled in the art. The two modulated optical carriers **22** and **56** are subsequently de-multiplexed at the remote site onto separate PM optical fibers using the well-known WDM techniques.

By virtue of the low-loss optical fibers, this invention allows the lasers and local oscillators to be separated by as much as 10 km, or more, from the remainder of the system.

Thus, this system may be implemented using a more remote antenna site, which is advantageous to many commercial communication and radar applications.

Further, this invention maintains a known phase relationship between the local oscillators **16** and **56** and the received Rf signal **13**. This allows the image rejection system to be used in direction finding systems.

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

Inventors: Ward et al.
Serial No.

PATENT APPLICATION
Navy Case No. 79,800

ABSTRACT OF THE INVENTION

An image rejecting microwave photonic downconverter uses a microwave sub-carrier modulation technique without concern for image frequency interference in the shifted signal, thereby allowing telecommunications systems to downconvert densely multiplexed communications channels into a low frequency band where conventional electronics can perform signal-processing functions. Using the image rejecting microwave photonic downconverter incoming microwave signals can be processed without ambiguity in direction finding applications, allowing remotable, multioctave microwave signal processing for frequency and phase determination. Two lasers providing separate optical carriers that are modulated by separate electro-optic modulators with sinusoidal electrical signals generated by separate local oscillators; are transmitted independently through two polarization-maintaining (PM) optical fibers of arbitrary length to a distant point. There the first modulated optical carrier is converted to an electrical domain and mixed with an input from an ultra-broadband radio frequency (RF) antenna receive-array, shifting the entire RF band to a higher frequency band equal to the original RF plus the modulation frequency of the first optical carrier. This upshifted frequency band is amplified and passed through a band-pass filter to attenuate frequencies outside the up-converted pass-band. The filtered signal is optically mixed with the modulated optical carrier modulated by the second local oscillator and the resulting intermediate frequency (IF) modulated optical carrier is detected using a second photodetector and transmitted to an electrical output port of the system.

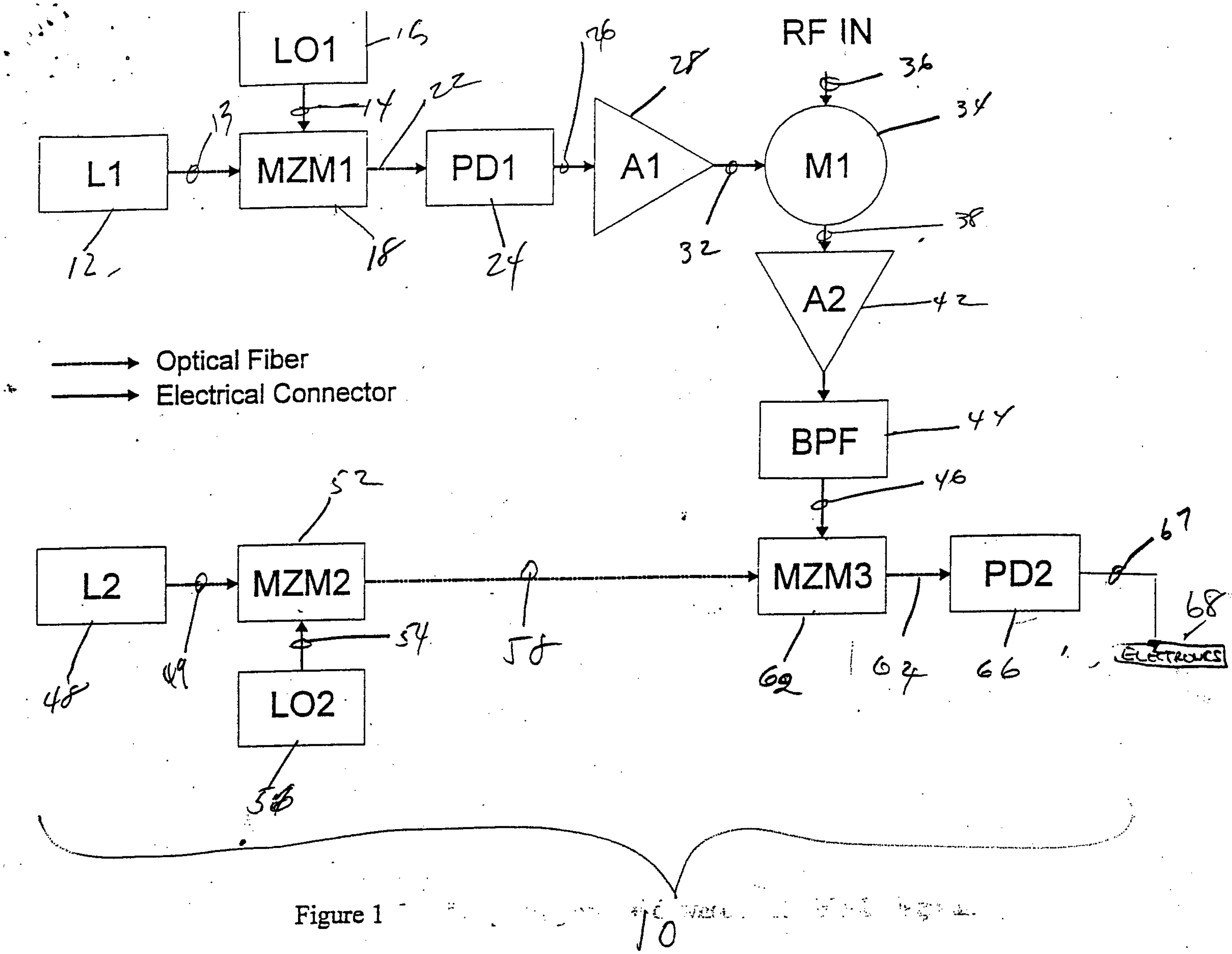

LO1
L1
MZM1
PD1
A1
RF IN
M1
A2
BPF
Optical Fiber
Electrical Connector
L2
MZM2
MZM3
PD2
LO2
ELECTRONICS

Figure 1

Figure 2(a)

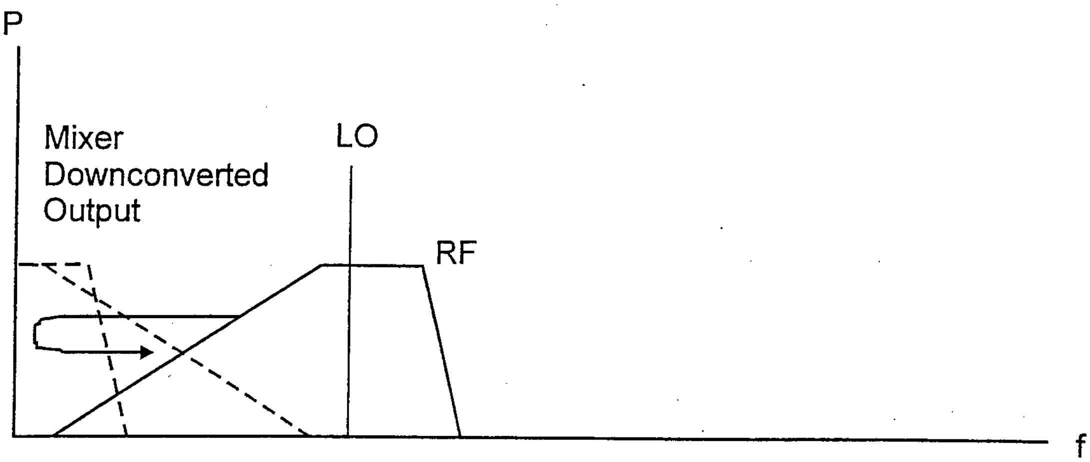


Figure 2(b)

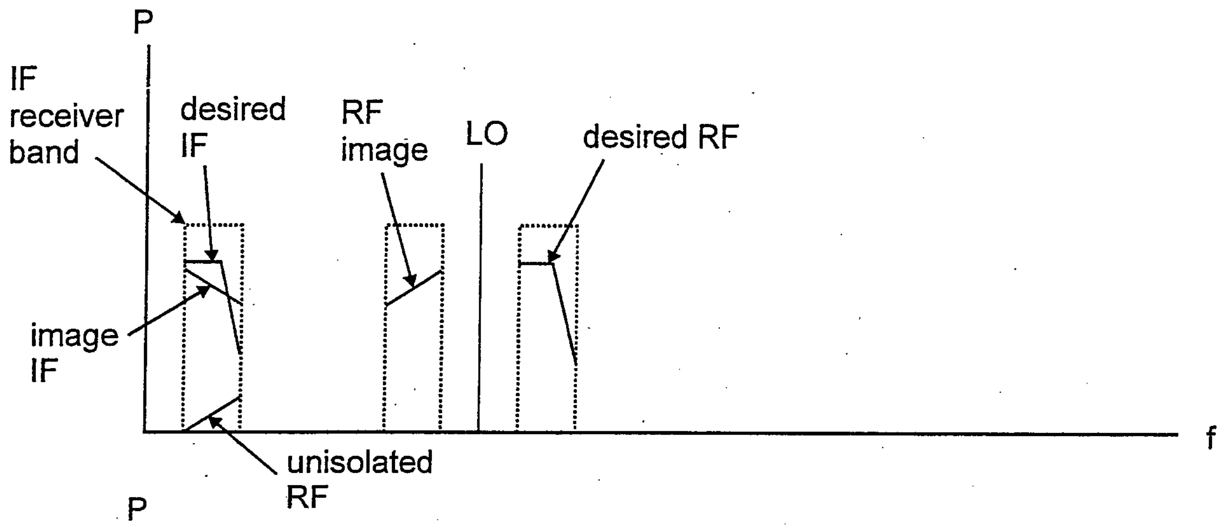


Figure 2(c)

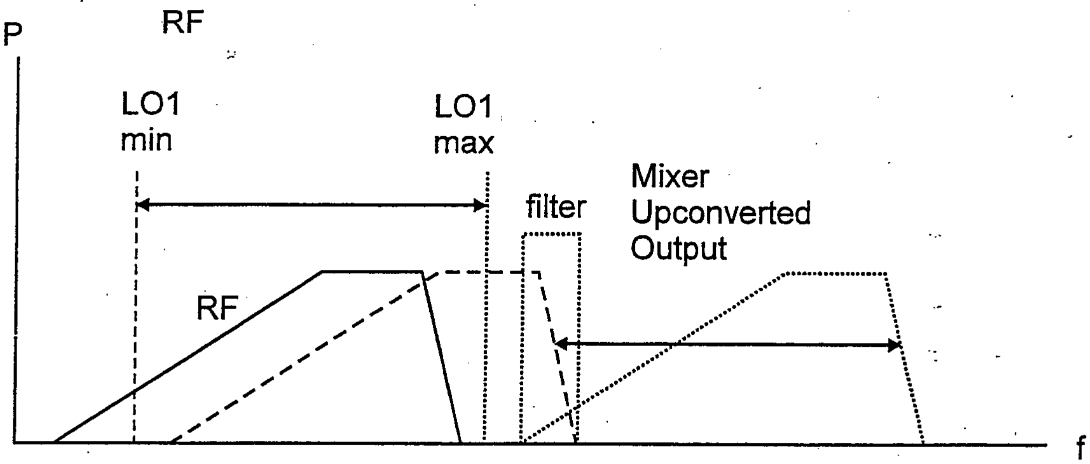
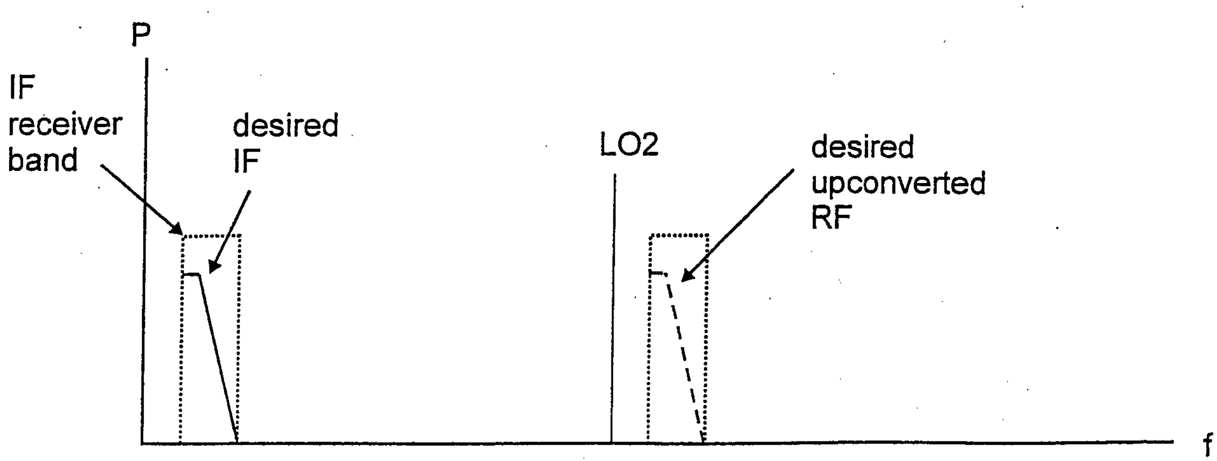


Figure 2(d)



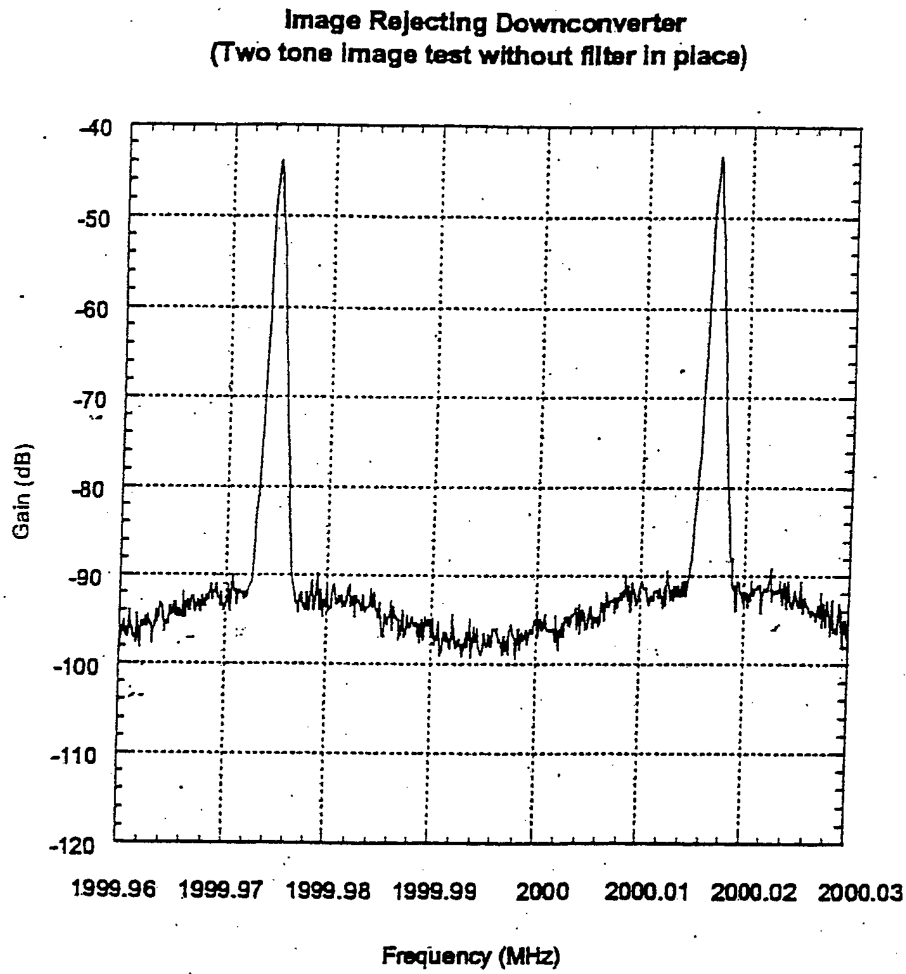


Image Rejecting Downconverter
(Two tone image test without filter in place)
-40
-50
-60
-70
-80
-90
-100
-110
-120
Gain (dB)
1999.96
1999.97
1999.98
1999.99
2000
2000.01
2000.02
2000.03
Frequency (MHz)

Figure 3

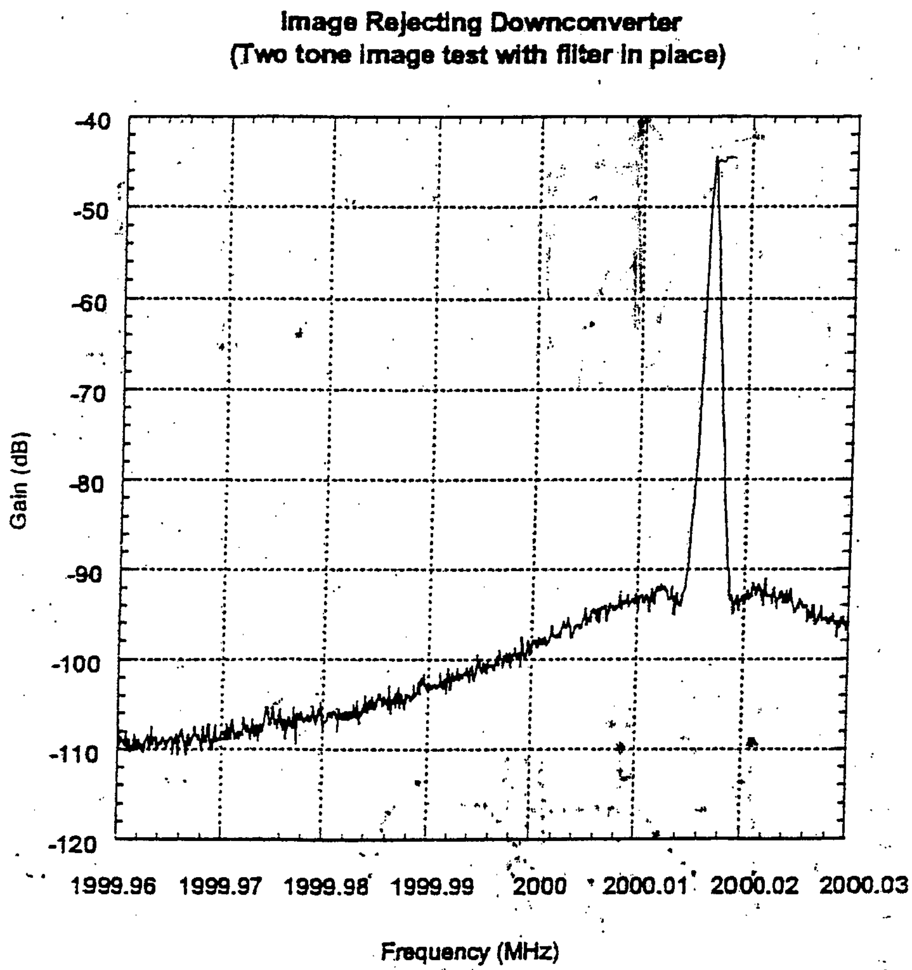


Image Rejecting Downconverter
(Two tone image test with filter in place)
-40
-50
-60
-70
-80
-90
-100
-110
-120
Gain (dB)
1999.96
1999.97
1999.98
1999.99
2000
2000.01
2000.02
2000.03
Frequency (MHz)

Figure 4