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ELECTRO-OPTICAL BROADBAND MICROWAVE FREQUENCY SHIFTER

BACKGROUND OF THE INVENTION

Field of the Invention

This invention provides, generally, an apparatus and method for arbitrarily shifting the frequency of an incoming electromagnetic signal. More specifically, this invention pertains to the use of an optical source to up-convert, filter, and downconvert an input electromagnetic signal in the microwave spectrum to shift the frequency of the electromagnetic signal that is output.

Description of the Related Art

Currently microwave frequency shifters rely primarily on digital phase shifters for creating a Serrodyne modulation format which results in a one-directional frequency shift, or the use of image rejection mixers which divide, modulate and recombine the signal, with the undesirable components (sidebands and carrier) removed by coherent cancellation. In the case of the digital phase modulator, the achievable image and carrier rejection is limited by the number of discrete bits that can be implemented in hardware, usually less than ten. This limits the

achievable rejection to below 25 dB. In the case of the image

rejection mixer, the achievable image and carrier rejection is

limited by the ability to create two broadband microwave signals

exactly 90° out of phase with exactly the same amplitude

(independent of the incoming frequency). Typical devices with 3°

phase error and a 0.25 dB amplitude imbalance are limited in

their image and carrier rejection to 30 dB.

A summary of image rejection versus phase and amplitude

imbalance is shown in **Figure 1**. Note that the phase error of

less than 1° with no amplitude error is necessary for greater

than 40 dB rejection. Further details of Serrodyne modulation is

to be found in Klein et al.; The DIGILATOR, a New Broadband

Microwave Frequency Translator; IEEE Transactions on Microwave

Theory and Technology; Vol MTT-15, No. 3; pp. 172-179; March

1967; Cummings, The Serrodyne Frequency Translator; Proceedings

of the IRE; Vol. 45, No. 2; pp. 195-186; February 1957; Thylen et

al.; Electro-Optical Serrodyne Frequency Translator for $\lambda=1.3\mu$m;

IEEE Proceedings, Vol. 132 Pt.J, No. 2; pp. 119-121; April 1985;

Johnson et al.; Serrodyne Optical Frequency Translation with High

Sideband Suppression; Journal of Lightwave Technology; Vol. 6,

No. 1; pp. 109-112; January 1988; and further details of image

rejection mixers can be found in the commercial literature of

Merrimac Industries, West Caldwell, NJ for the Model Numbers SSF-

2; SSP-1R, SSF-1E, SSP-2, SSM Series and SSB Series Single

sideband modulators.

In general, electrical frequency shifters can operate only over a very narrow bandwidth due to engineering complexities. In the case of the single-sideband mixer, it becomes very difficult to phase and amplitude match over a broad bandwidth, therefore the presently available devices are usually limited to instantaneous bandwidths of less than 1-2 octaves at microwave frequencies. In the digital phase shifter, the trade off between creating many bits for good rejection is not compatible with broadband operation because of the many paths the signal takes, therefore the current devices are usually limited to instantaneous bandwidths of less than 12 GHz.

The fundamental ideas used in this invention of up-converting, filtering and downconverting to shift the microwave frequency has been achieved by the use of all-microwave components, as shown in **Figure 2**. An incoming microwave signal, f_{sig}, **12** is mixed with a microwave oscillator **14** having a frequency, f_{lock}, in an up-converting double balanced mixer. The positive frequency component (upper sideband, USB) of the incoming signal **12** is frequency converted to $f_{lock} + f_{sig}$ and the negative frequency component (lower sideband, LSB) of the incoming signal **12** is frequency converted to $f_{lock} - f_{sig}$. An electrical filter **18** attenuates either the shifted LSB or the shifted USB, as well as the incoming signal **12** and the mixing frequency, f_{lock}. After mixing in the mixer **16**, only the wanted (shifted) single sideband at the IF input, I, is applied to a downconverting mixer

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22. A signal generated by a second oscillator 24, f_a, is mixed with the shifted sideband in the mixer 22 to produce a signal with a new frequency $f_a - (f_{lock} - f_{sig})$, where the LSB is used without loss of generality. If $F_a - f_{lock}$ is nonzero (if the oscillator at the frequency f_a has a slightly different frequency than f_{lock}), the resulting signal at f_{sig} is shifted by $f_a - f_{lock}$. An example is where a 10.5 GHz input signal frequency is mixed with a 12 GHz oscillator to create frequencies of 1.5 and 22.5 GHz. A 5 GHZ low pass filter removes the original 10.5 GHz signal, the 12 GHz local oscillator and the 22.5 GHz shifted USB, leaving only the shifted LSB. The shifted LSB at 1.5 GHz is then upconverted in a second mixed with a 12 GHZ + 500 Hz oscillator to a net shifted output frequency of 10.5 GHz + 500 Hz. The results of this is shown in **Figure 3**. If a traditional Serrodyne or image rejection mixer were used there would be unwanted signals (images) at 10.5 GHz ± (n+1)*500 Hz, where n is a nonzero integer. The 63 dB carrier rejection and approximately 60 dB of image and spurious rejection shown in **Figure 3** is possible since the level of image and carrier rejection is determined by the level of filtering used between the mixers, this may be very high (>100 dB). The drawback of all the microwave technique presented above is that to achieve wideband operation, a mixer with wide bandwidths on all three ports is required. Additionally, the intermodulated distortion products of electrical mixers are quite high and can lead to significant signal distortion.

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This invention presents an apparatus and technique to obtain a frequency shifted microwave signal by utilizing electrically controlled optical phase shifters to create a serrodyne modulation or multiple offset-phase-locked lasers to shift the microwave signal to a new frequency. This results in an improved image and carrier rejection when compared to electrical techniques.

SUMMARY OF THE INVENTION

The object of this invention is to provide an apparatus and method for arbitrarily shifting the frequency of an incoming microwave signal with large instantaneous bandwidth.

Another object of this invention is to provide an improved output image and carrier rejection that will allow many microwave signal processing functions.

These objectives are achieved by the broadband microwave frequency shifter which is a electro-optical device that accomplishes frequency shifting, or translation, in one embodiment, by the use of serrodyning techniques, with a plurality of optical signals. A first optical signal is modulated with the radio frequency signal desired to be translated and processed to produce an upconverted lower sideband

optical signal. A frequency shifted optical signal is generated by either using an optical phase shifter utilizing serrodyning techniques to frequency shift a second optical signal or by offset-phase-locking a third optical signal to an upshifted second optical signal. When the frequency shifted optical signal is combined with the first optical signal, which is amplified modulated by the upconverted input radio signal, it is converted to an output radio frequency signal thereby producing an output microwave signal that duplicates the input microwave signal in all aspects except that its center frequency has been shifted.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a plot of image rejection for a given phase and amplitude imbalance.

Figure 2 shows a typical microwave equivalent frequency shifter.

Figure 3 shows the typical performance of the microwave equivalent frequency shifter.

Figure 4 shows a basic optical configuration for implementing wideband optical serrodyne microwave frequency shifting.

Figure 5a shows combined AM optical signal as a result of the mixing products between the amplitude modulated first laser and the continuous wave (CW) second laser of the wideband optical serrodyne microwave frequency shifter before photodetection and subsequent filtering by a bandpass filter.

Figure 5b shows the combined AM optical signal as the result of the mixing products between the amplitude modulation first laser (modulated with the upconverted RF signal) and the continuous wave (CW) second laser(phase modulated by the optical phase modulator with serrodyne signal input) of the wideband optical serrodyne microwave frequency shifter before photodetection and subsequent filtering by a bandpass filter.

Figure 6 shows a basic optical configuration for implementing wideband optical microwave frequency shifting utilizing three lasers.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In the basic configuration of the preferred embodiment for implementing wideband optical microwave frequency shifter 10, as shown in Figure 4, where two phase-lockable lasers 26 and 28 are used to generate optical signals. Preferably, these lasers 26 and 28 are Nd:YAG lasers, however, other laser types may be

utilized.

A first portion of the optical signal generated by the first laser **26** output is applied to a second coupler **38** from a first coupler **34**. A first portion of the optical signal from the second laser **28** is also applied to the second coupler **38** from a third coupler **36** to produce a combined optical signal output. This combined optical signal is incident on a first photodetector **42** which converts it to an output radio frequency (RF) signal producing the laser offset locking frequency. This signal is fed back to the second laser **28**, after mixing in mixer **44** with a sinusoidal frequency source **32** oscillating at the locking frequency, f_{lock}, from an external sinusoidal frequency source **32**. The output of the mixer **44** is the phase error between the laser RF beatnote, or laser offset locking frequency, and the frequency source **32**. This signal phase locks the phases of the two lasers **26** and **28** to the sinusoidal frequency source **32** through a phase lock loop **46**.

The second output of the first optical coupler **34** and the second optical coupler **36** are further divided into two approximately equal parts by a fourth and fifth optical coupler **54** and **56**, respectively. A first output of the fourth optical coupler **54** is amplitude modulated (AM) in a optical modulator **62**, preferably a Mach-Zehnder, with an RF signal **58** to be translated,

f_{RF}, and combined with a first output of the fifth optical

coupler 56 to produce a combined amplitude modulated optical

signal. The frequency components are shown in Figure 5a, before

photodetection and subsequent filtering by bandpass filter 72.

The combined AM optical signal is applied to a second

photodetector 68, the output of the which consists of the mixing

products between the amplitude modulated first laser 26 and the

continuous wave (CW) second laser 28.

The only requirement is that the laser offset locking

frequency output by the photodetector 42 must be greater than the

highest frequency component of the RF input signal 58 to be

translated. The upper sideband of the RF input signal 58 is

frequency down-shifted to $f_{lock} - f_{RF}$ and the lower sideband (LSB)

of the RF input signal 58 is frequency upshifted to $f_{lock} + f_{RF}$.

The RF output of the photodetector 68 consists of the unshifted

RF signals from the amplitude modulated first laser 26, the CW

tone at the locking frequency, f_{lock}, from the first laser 26 and

second laser 28, and the up- and down-shifted sidebands of RF

input signal 58. The upconverted LSB is the desired term which

is filtered in a bandpass filter 72 and amplified in a high

frequency (HF) amplifier 74. The up-shifted LSB is then used to

amplitude modulate the second optical signal of the first laser

26 appearing at the second output of the third optical coupler in

a second Mach-Zehnder modulator 76 which is applied to a sixth

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optical coupler 78.

The output of the second Mach-Zehnder modulator 76 is then

combined with a processed signal of the optical output of the

second laser 28. The processed signal of the second laser 28 is

obtained by applying the second output of the third optical

coupler 56 which appears as a second output of the fifth optical

coupler 56 to an optical phase shifter 82.

By applying a serrodyne signal 84 from an external serrodyne

signal input device 94 to the optical phase shifter 82, the

frequency of the RF out of the third photodetector 86 can be

shifted either up or down. The necessary optical phase shift to

result in a 2π microwave phase shift for creating a frequency

shift with high carrier and sideband rejection is only 2π radians

at the optical frequency. The output of the optical phase shifter

82 is combined in the sixth optical coupler 78 with the output of

the second Mach-Zehnder modulator 76 and applied to a third

photodetector 86 producing an electrical signal which is filtered

in a bandpass filter 88 to produce an output radio frequency

signal 92 which is similar in all characteristics to the input

radio frequency signal 58 except that its carrier frequency has

been shifted.

No frequency shifting occurs when no external signal is

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applied to the optical phase shifter **82**. In this condition, the RF output of the third photodetector **86** consists of the AM demodulated shifted signal from the amplitude modulated first laser **26** (via the second Mach-Zehnder modulator **76**), the CW tone at the locking frequency from the first and second lasers **26** and **28**, respectively, the frequency down-shifted USB (f_{lock} - (f_{lock} - f_{RF})) = f_{RF}, and the up-shifted lower sideband (LSB) to $2*f_{lock}$ + f_{RF}. The downconverted USB (the USB is the up-converted LSB from the output of the second photodetector **68**) is the desired signal and is filtered out by the bandpass filter **88**.

The basic configuration of the microwave frequency shifter may be modified, as shown in another preferred embodiment **20**, where even higher image and sideband rejection may be obtained with the addition of a third laser **96**, as shown in **Figure 6**. The first portion of an optical signal from the third laser **96** from optical coupler **106** is combined with a portion of the optical signal from the second laser **26** in coupler **56** and the combined optical signal is converted to an electrical signal in a photodetector **112** and phase locked to the second laser **26** by the desired frequency shifting amount, f_{shift}, from an external frequency source **98**, through a mixer **102** and phase locked loop **104**.

The upconverted lower sideband output from photodetector **68**

is the same as described in the previous embodiment and is the
desired term to be filtered in bandpass filter 72 and amplified
in high frequency amplifier 74. This signal modulates the first
laser 26 as in the first embodiment, however, in this embodiment,
the output of modulator 76 is combined with the third laser 96.
The upconverted lower sideband at frequency ($f_{lock} + f_{sig}$) is
downshifted to ($f_{sig} + f_{shift}$) or ($f_{sig} - f_{shift}$) depending on whether
the third laser 96 frequency is higher or lower than that of the
second laser 28. This embodiment improves the sideband and
carrier rejection because it replaces the serrodyne shifted
second laser 28 (which has a residual carrier and many unwanted
sidebands) with another single frequency laser 96 which tracks
the frequency of the second laser 28 (by an offset frequency
f_{shift}) by a phase locked loop.

Basically, this embodiment replaces the serrodyne shifted
second laser 28 with a third laser 96 offset in frequency (via
offset phase locking) from the second laser 28 frequency.
(Serrodyning being a technique for shifting the frequency of a
laser or microwave signal.) The technique in this embodiment has
a better performance than the serrodyne technique because the
serrodyne technique creates unwanted residual carrier and
sidebands besides the shifted frequency component. This is a
consequence of the non-ideal serrodyne sawtooth waveform
generation or modulation of the desired frequency.

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The image rejection obtainable by this embodiment 20 is similar to the prior art all microwave frequency shifter, where the rejection is determined by the amount of filtering and not the purity of the serrodyne signal. However, this embodiment is limited in the speed at which the shifting frequency can be adjusted.

The devices described above provide a broadband instantaneous response limited only by ~ 1/2 the available optical modulator bandwidth and reduces the required optical phase shift for implementing Serrodyne modulation by greater than four orders of magnitude. Frequency shifting at gigahertz rates of two to four orders of magnitude greater than the prior art are produced by this techniques used in this device.

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

ABSTRACT

The broadband microwave frequency shifter is an electro-optical device that accomplishes frequency shifting, or translation by the use of serrodyning or mixing techniques. A first optical signal is modulated with the radio frequency signal desired to be translated and processed to produce an upconverted lower sideband optical signal. A second optical signal is frequency shifted using an optical phase shifter utilizing serrodyning techniques or by offset phase locking it to another optical signal. When the frequency shifted optical signal is combined with the upconverted optical signal and converted to an output radio frequency signal thereby producing an output microwave signal that duplicates the input microwave signal in all aspects except that its center frequency has been shifted.

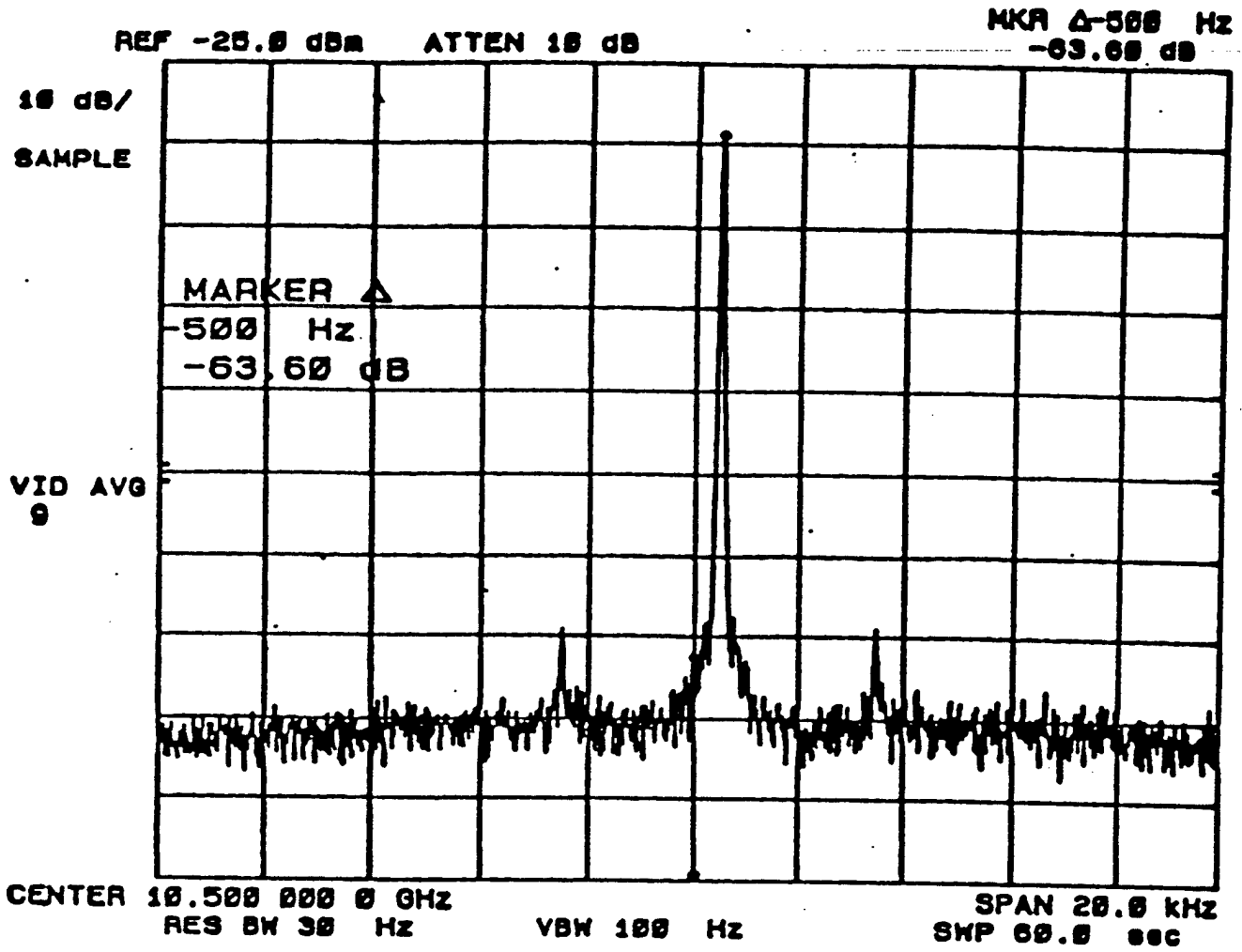# IMAGE REJECTION

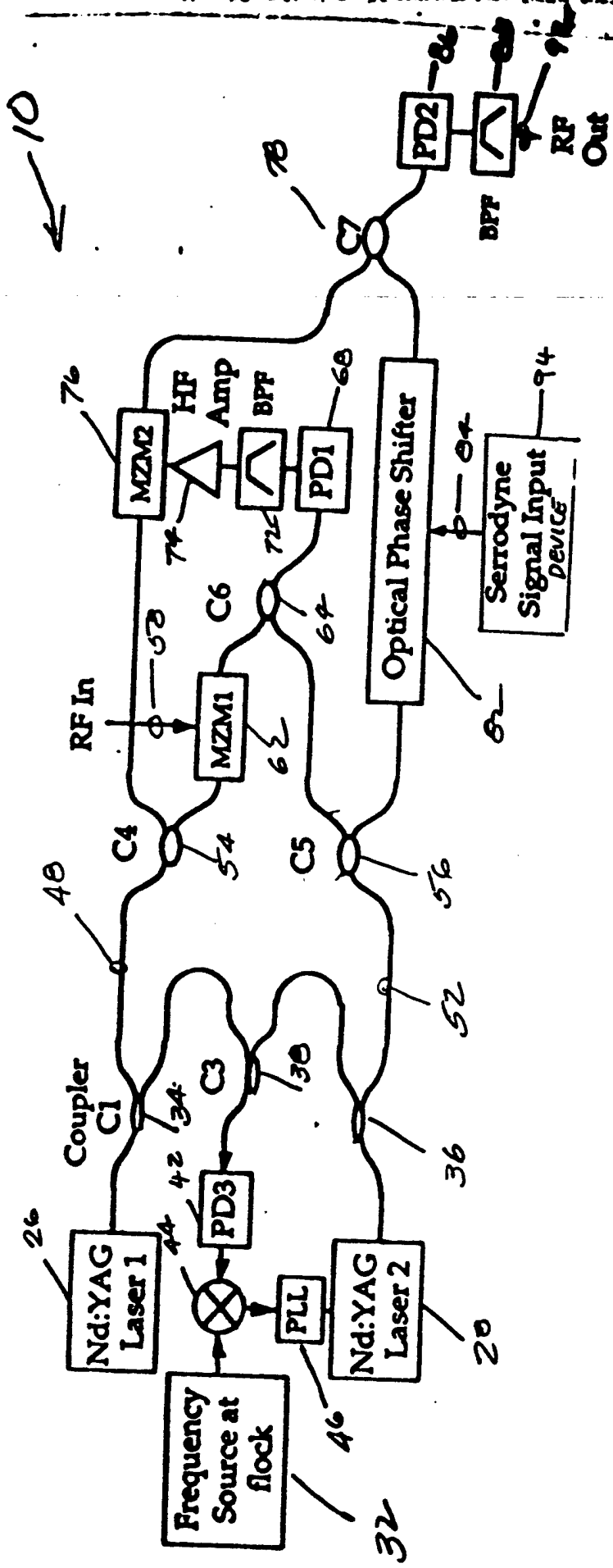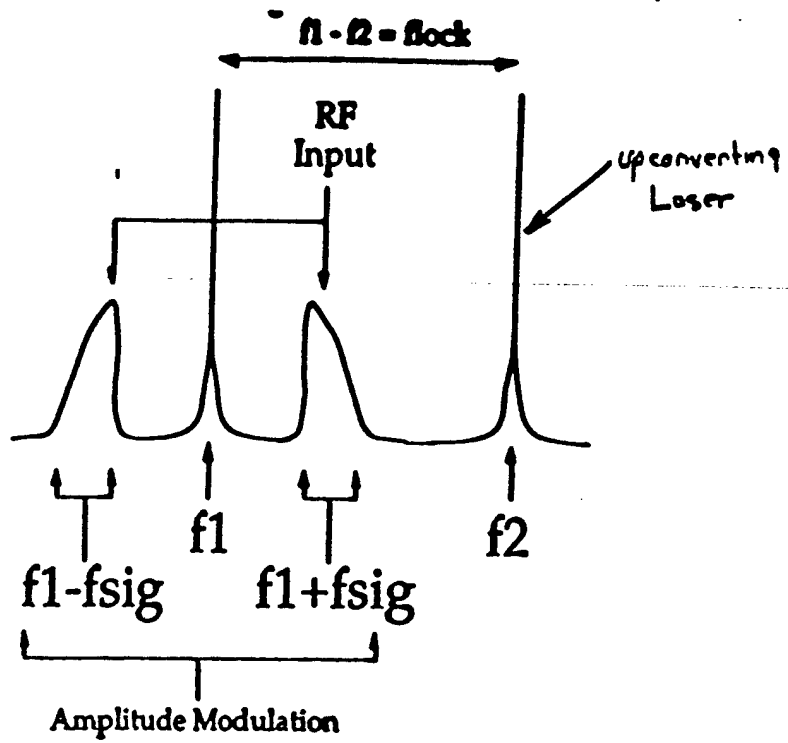for a given Amplitude and Phase Balance
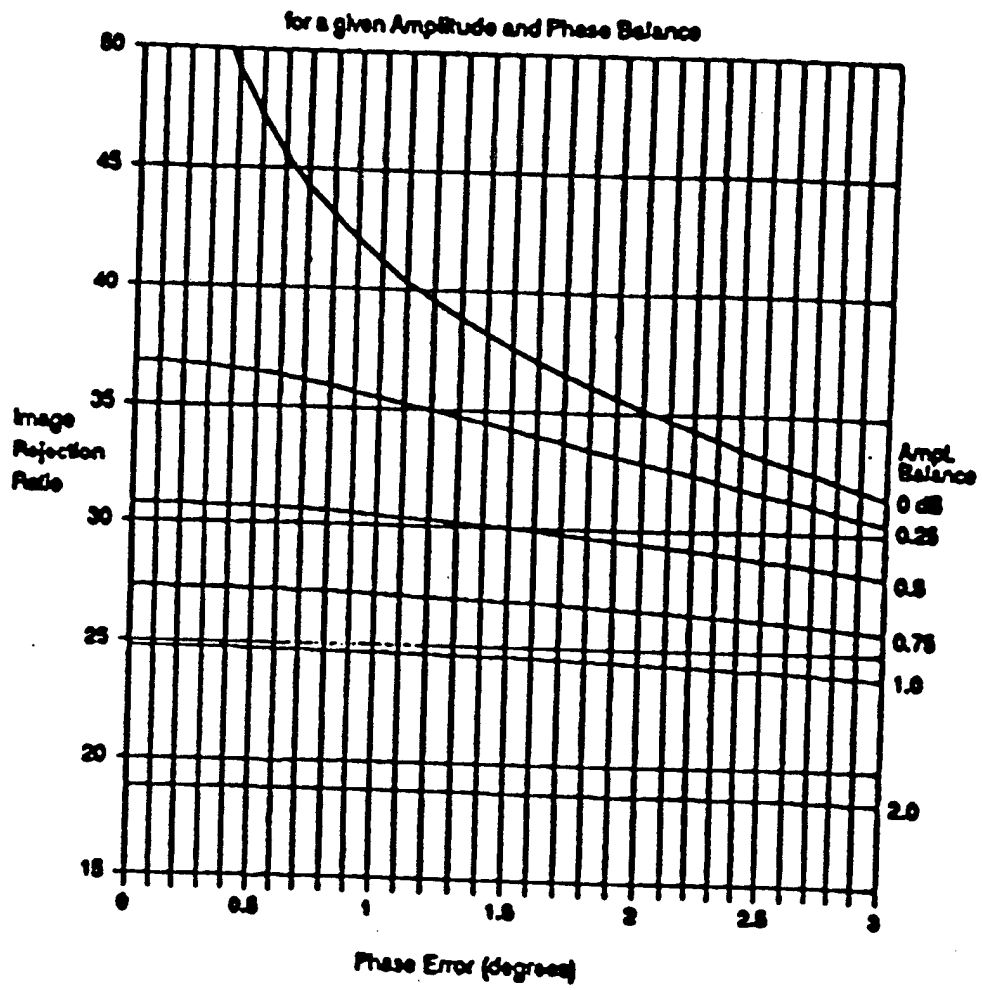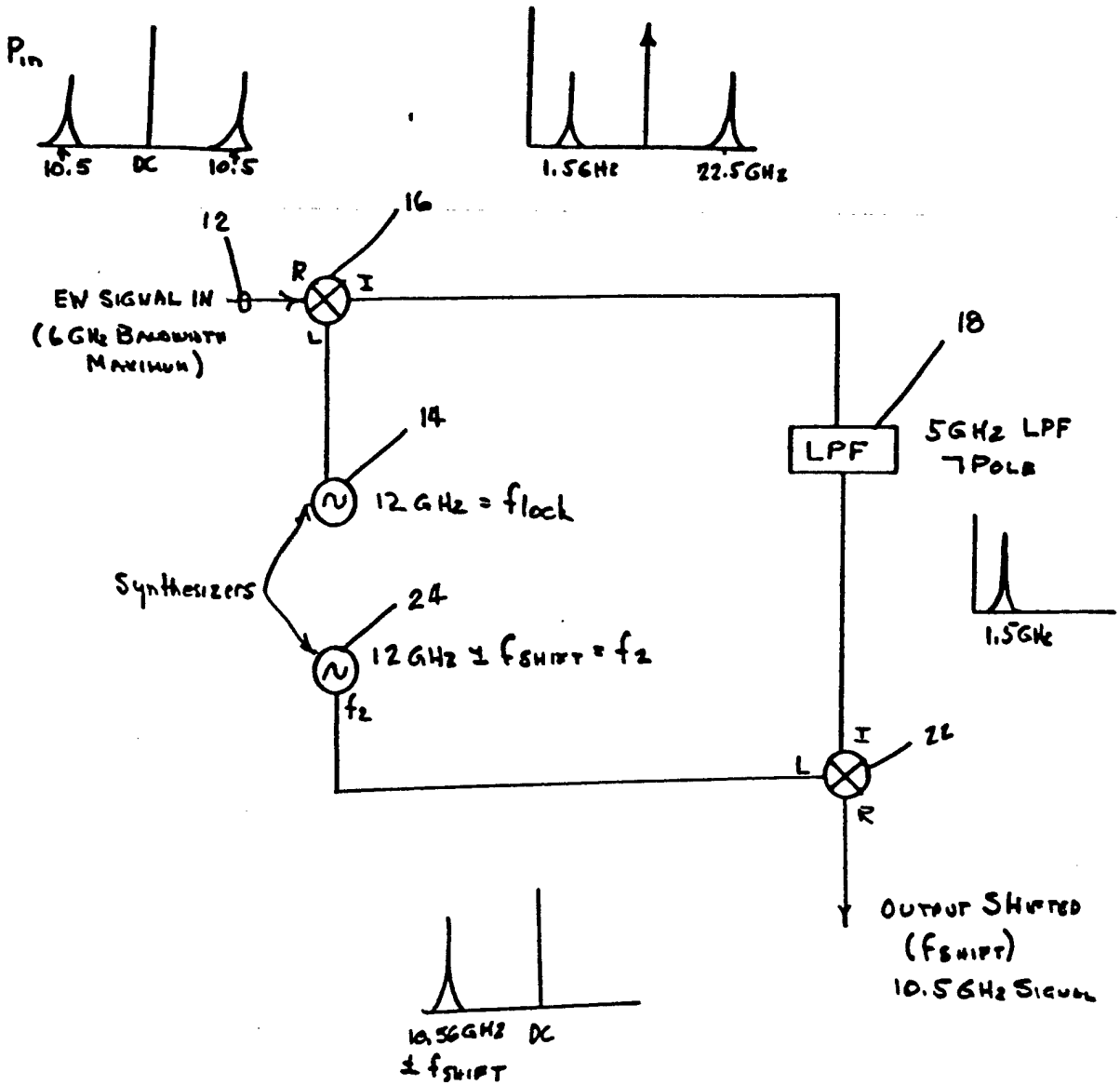
FIGURE 1

Figure 2
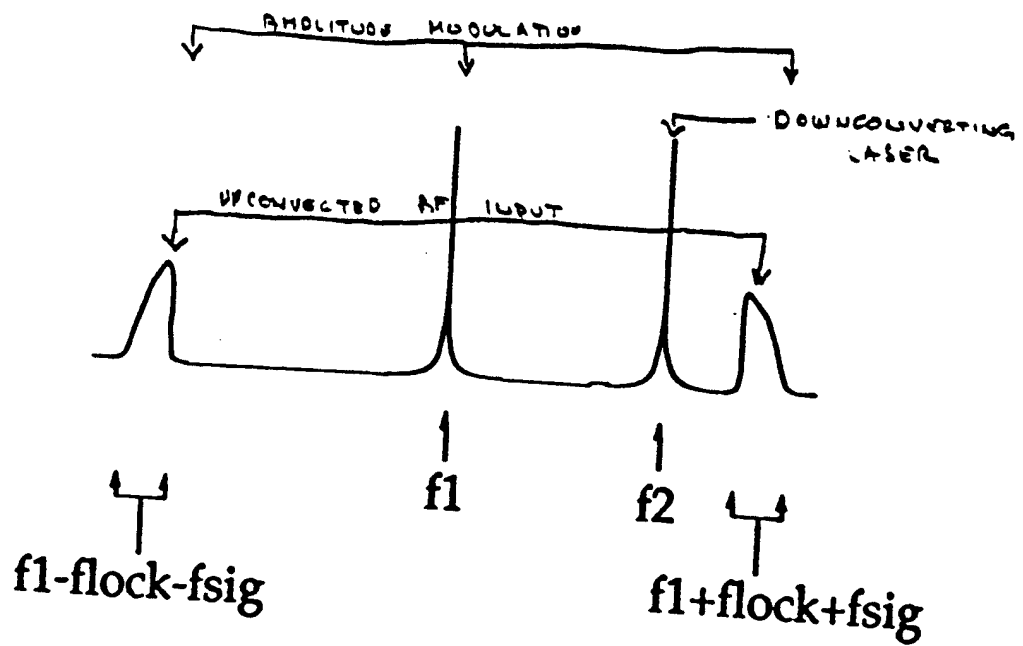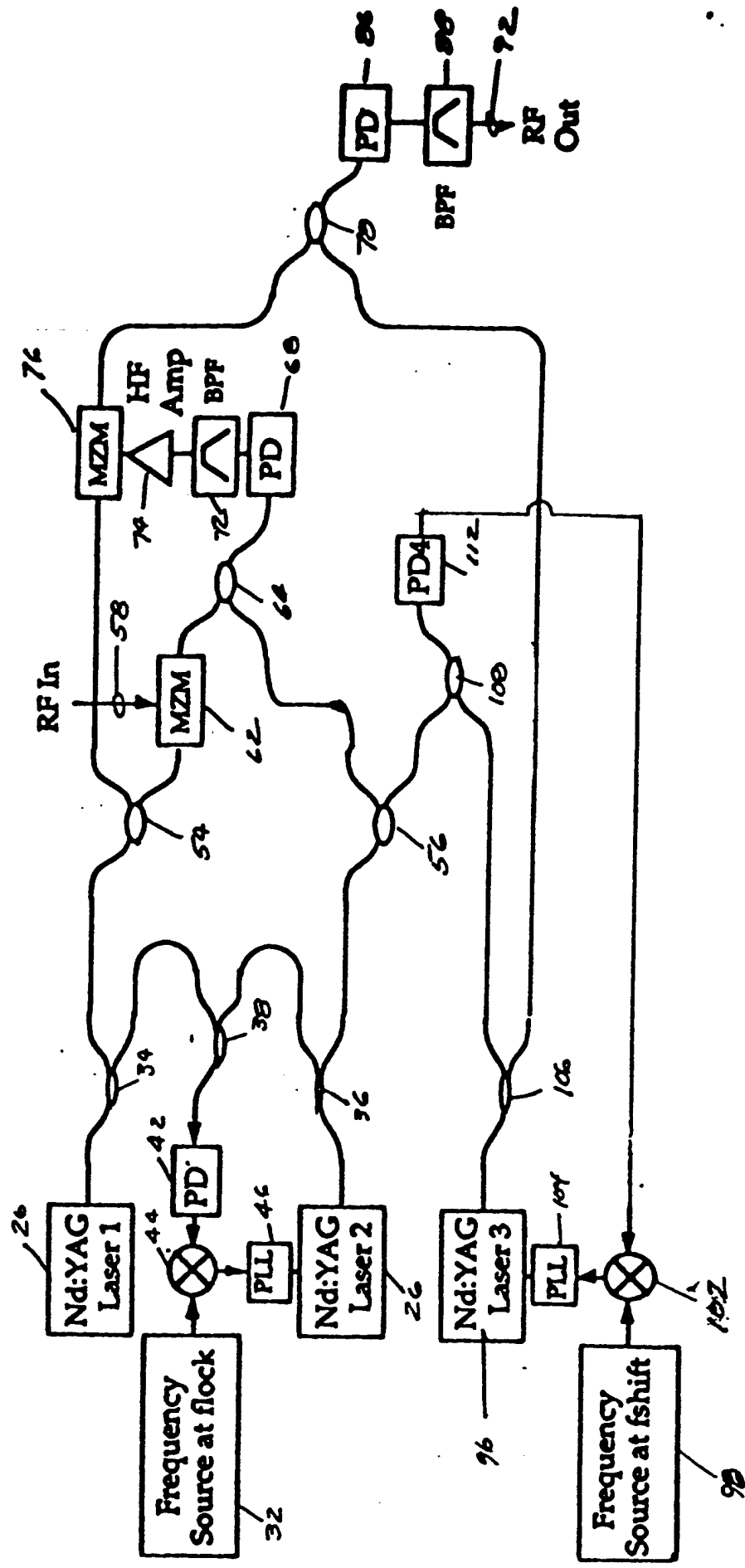
PRIOR ART

FIGURE 3

FIGURE 4

Figure 5(a)

Figure 5(b)

Figure 6