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Inventor: Nichols et al.
Serial No.

PATENT APPLICATION
Navy Case No. 79,759

WIDEBAND SINGLE SIDEBAND MODULATION OF OPTICAL CARRIERS

BACKGROUND OF THE INVENTION

Field of the Invention

This invention pertains generally to radio frequency (RF) transmission over optical carriers and more specifically to the generation of single sideband signals with suppressed carrier over a wide RF bandwidth for transmission over optical fibers.

Description of the Related Art

In electronic communications, single sideband (SSB) transmission is a well-known technique for reducing bandwidth and power requirements as well as "fading" due to dispersive transmission environments. When combined with carrier suppression (SC), this technique can enhance link gain in an amplified system. These benefits can be similarly realized in photonic links where RF signals are multiplexed onto an optical carrier and transmitted via a fiber optic cable, which has advantages over coaxial cable in terms of bandwidth, incremental loss, and electromagnetic interference (EMI) immunity. For micro- and millimeter- wave modulation frequencies, SSB becomes a useful way of overcoming fiber chromatic-dispersion effects (Fading in the fiber) while also suggesting new applications outside communications. (**SEE**, Smith et al., OVERCOMING CHROMATIC-DISPERSION EFFECTS IN FIBER-WIRELESS SYSTEMS INCORPORATING EXTERNAL MODULATORS, IEEE Trans. Microwave Theory Tech., Vol. 45, pp. 1410-1415, 1997.)

From communications theory, it is well known that a small-signal phase- or amplitude-modulated (PM or AM) carrier will appear on a spectrum analyzer as shown in **Figure 1a**. This double sideband (DSB) spectrum can be easily generated using a laser and an electro-optic phase or amplitude modulator (two phase modulators combined in a Mach-Zehnder configuration) driven by an RF generator. In a Mach-Zehnder modulator, depending upon modulator bias and the relative phase of the RF inputs, the phase relationship between the three peaks can be a combination of those relationships illustrated by the phasor diagram **Figure 1b**. With the carrier as a reference phasor, the sidebands will rotate in opposite directions: if they are phased such that the total sideband phasor is always parallel or antiparallel to the carrier, then the result will be AM; if they are phased such that the total sideband phasor is always perpendicular to the carrier, then the result will be mostly PM with a small amount of AM. True PM is comprised of additional harmonic sidebands such that the resultant (carrier plus sidebands) actually swings in pendulum fashion with constant amplitude.

Chromatic dispersion is a well-known limitation on the transmission distance achievable in photonic (optical carrier-based) links. While recognized for some time as a problem for digital systems, recent interest has been driven by the wireless/mm-wave market. (**SEE**, Yonenaga et al., A FIBER CHROMATIC DISPERSION COMPENSATION TECHNIQUE WITH AN OPTICAL SSB TRANSMISSION IN OPTICAL HOMODYNE DETECTION SYSTEMS, IEEE Photon. Technol. Lett., Vol. 5, pp. 949-951, 1993; Smith et al., *opcit.*, Hofstetter et al., DISPERSION EFFECTS IN OPTICAL MILLIMETER-WAVE SYSTEMS USING SELF-HETERODYNE METHOD FOR TRANSPORT AND GENERATION, IEEE Trans. Microwave Theory Tech., Vol. 43, pp. 2262-2269, 1995; Gliese et al.,CHROMATIC DISPERSION IN FIBER-OPTIC MICROWAVE AND MILLIMETER-WAVE LINKS, IEEE Trans. Microwave Theory Tech., Vol. 44, pp. 1716-1724, 1996; and Park et al., ELIMINATION OF THE FIBRE CHROMATIC DISPERSION PENALTY ON 1550 NM MILLIMETER-WAVE OPTICAL TRANSMISSION, Electron. Lett.. Vol. 33, pp. 512-513.) Dispersion D (in ps/km-nm) results in a differential phase delay $\phi = \pi D\lambda^2 L f^2/c$ between one spectral component at wavelength λ and another such that the difference increases linearly with distance L and quadratically with the frequency separation f. (**See**, Gliese, opcit.) Referring again to **Figure 1b**, this means that the oscillation direction of the total sideband phasor rotates linearly with L, periodically transforming AM to PM and back. For an intensity-modulated direct-detection (IM-DD) link, this results in a sinusoidal variation of link gain with L. The frequency response at a particular length will also be sinusoidal with quadratically increasing "phase". (**SEE**, Smith and Park, *opcit.*)

If a SSB scheme is used to eliminate one of the sidebands, the other sideband will rotate alone, producing a combination of AM and PM of lesser amplitude. The phase-insensitive DD receiver will then recover the AM without the periodicities associated with carrier-to-sideband dispersion. It is noted that this is not generally a complete solution to the dispersion problem. If the single-sideband is sub-carrier modulated (SCM) or the optical carrier is baseband modulated with a large enough information bandwidth, the information itself will be "dephased" over the fiber length. (SEE, Hofstetter, and Yonenaga, *opcit.*) Over a large distance, the optical linewidth shared by the carrier and the sideband is also decorrelated resulting in increased phase noise. (SEE, Gliese, *opcit.*) There are a variety of optical techniques (e.g., chirped gratings, dispersion-compensating fiber) which can be applied to reduce this effect.

Some techniques for photonic SSB generation involve elimination of one sideband from a DSB output. These include using a fiber Bragg grating (FBG) notch filter or, in the case of baseband modulation, using a Mach-Zehnder-type filter with a ring resonator on one arm to obtain a sharp cutoff band-reject filter. (**SEE**, Park and Yonenaga. *opcit.*) Another technique treats the DSB-SC output of a null-biased Mach-Zehnder modulator (MZM) as a SSB output with twice the modulation frequency and utilizes a delay-line filter to separate and modulate only one sideband. (**SEE**, Hofstetter, *opcit.*) The difficulty with these techniques is that they require filter designs which are matched to the frequency separations of interest and are therefore limited in bandwidth.

An alternative approach is to generate SSB output via cancellation within a dual-drive MZM. As shown in **Figure 2a** and **2b** where the carrier phasors correspond to each arm of the device, if the modulator is biased at quadrature and the RF drives are π/2 out of phase, then either the upper or lower sidebands will cancel. This technique has been applied successfully to 80 km of fiber without dispersion-induced power degradation. (**SEE**, Smith, *opcit.*) This technique can be used with a traveling-wave modulator placed at the center of a polarization-maintaining (PolM) fiber loop joined by a PolM fiber coupler (a Sagnac interferometer) in order to supress the carrier as well. (**SEE**, Frankel et al., OPTICAL SINGLE-SIDEBAND SUPRESSED-CARRIER MODULATOR FOR WIDE-BAND SIGNAL PROCESSING; IEEE J. Lightwave Technol., Vol. 16, pp. 859-863, 1998.) The traveling-wave device generates sidebands more efficiently in the direction for which the RF signal and optical carrier are copropagating, thereby avoiding loop cancellation of the sidebands. Note that SSB with carrier can be recovered simultaneously (using a circulator) from the reflection port of the PolM fiber optic coupler. A problem with the single-MZM Sagnac SSB-SC configuration is that, because the sidebands propagate in the forward direction only, true carrier cancellation can only be achieved at a single RF power level, limiting the range of usable drive levels.

Integrated optical devices utilize materials which have been processed to create light-guiding regions with cross-sectional dimensions approximating the light wavelength as structures for generation, manipulation, and detection of light wave (SEE, Hutcheson et al., INTEGRATED OPTICAL CIRCUITS AND COMPONENTS, Dekker; New York; 1987.) As such a material, LiNbO3 is a common substrate because of its excellent electro-optical and waveguiding properties. In commercial optical modulators, this material is inlaid with waveguides typically using either an impurity in-diffusion or ion exchange method. Depending upon the surface orientation of the crystal substrate, electrodes are laid out directly above or above and beside the waveguide to influence the phase of the lightwaves propagating therein via the electro-optic effect. Such a device, with a single waveguide acts as an electrically-driven optical phase modulator and can be butt-coupled to fiber pigtails for integration into fiber optic systems. In other devices, the waveguides in these modulators are laid out in a splitter-parallel-combiner sequence to form a Mach-Zehnder interferometer, wherein the applied field influences the relative phase between the lightwaves propagating in the parallel arms. Thus, an applied electrical RF signal can induce an optical intensity fluctuation at the same frequency.

In order to improve the coupling efficiency of the electric field-optical field interaction at higher speeds, traveling-wave electrodes (microwave transmission lines parallel to the optical waveguides) are used instead of bulk (area, capacitor-like) electrodes. Designs which improve the propagation velocity match between the electrical and optical waves also enhance coupling efficiency and thereby improve modulation bandwidth. Because of the velocity match property, light in such devices is modulated more efficiently in one propagation direction than the other. For reference, this is called the preferred direction of the modulator.

Intensity (amplitude) modulators can be fashioned with a single RF drive or dual RF drives. In the former device, the electrodes are typically designed such that an antisymmetric field is generated across both parallel arms to produce a "push-pull" relative phase modulation which preserves the average relative phase rather than using an independent set of electrodes to drive each arm as in the latter device. However, the same effect can be generated in the dual-drive MZM by driving its RF inputs with the same signal 180 degrees out of phase. This "push-pull" modulation is preferred because phase disturbance is undersireable in an amplitude modulator.

SUMMMARY OF THE INVENTION

The object of this invention is to provide an apparatus for generating single sideband optical signals with suppressed carrier over a wide radio frequency (RF) bandwidth and a wide range of RF power levels for use in optical fiber or free space transmission of electromagnetic and other information and for processing of RF signals.

These and other objectives are accomplished by the wideband single-sideband modulator for generating single-sideband (SSB) modulation with suppressed carrier which utilizes traveling-wave optical modulators (e.g., $LiNbO_3$ Mach-Zehnder) in a Sagnac loop. In the wideband single-sideband modulator, optical power from a polarized source is injected into polarization-maintaining fiber (PolMF) and it is split equally via a directional polarization-maintaining (PolM) fiber coupler, resulting in counterpropagating lightwaves in a Sagnac loop. These counterpropagating waves are $\pi/2$ out of phase due to the action of the coupler and remain so when they return to the coupler because they travel equal distances around the loop. Because the coupler is a reciprocal device, if the waves return to the coupler with equal amplitudes, they will recombine and exit the original input port toward the polarized light source. When light in each direction of the loop is properly phased and amplitude modulated, respectively, the optical carriers and one sideband (each) returning to the coupler will maintain equal amplitudes and exit the input port. Whereas, the other (single) sidebands will add in phase and exit the output port. The technique circumvents the problem of complete carrier cancellation over a range of radio frequency (RF) power levels, thereby serving as an enabling architecture for photonically-remoted ultrawide-band single-sideband suppressed-carrier (SSB-SC) modulated links.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1a shows an output power spectrum for phase or amplitude double sideband modulation.

Figure 1b shows the phase relationship between the three spectral peaks depending upon modulator bias and the relative phase of the RF input.

Figure 2a shows where the carrier phasors correspond to each arm of a dual-drive Mach-Zehnder modulator, if the modulator is biased at quadrature and the RF drives are π/2 out of phase.

Figure 2b shows the resultant phasor corresponding to the total output of the dual-drive Mach-Zehnder modulator, if the modulator is biased at quadrature and the RF drives are $\pi/2$ out of phase.

Figure 3a shows a wideband Sagnac interferometer dual-modulator configuration for single-sideband generation with carrier suppression.

Figure 3b shows a phasor diagram for the wideband Sagnac interferometer dual-modulator configuration for single-sideband generation with carrier suppression detailing the modulation phasors for each loop propagation direction.

Figure 3c shows a phasor diagram of the output from the Sagnac interferometer dual-modulator configuration for single-sideband generation with carrier suppression.

Figure 4 shows the measured output of the architecture described in **Figures 3a** and **3c**.

Figure 5a shows a monolithic electro-optic apparatus wherein the phase and amplitude modulators are combined into a single device.

Figure 5b shows a wideband Sagnac interferometer configuration wherein the device of **Figure 5a** has been placed at the center of a Sagnac loop.

Figure 6 shows a wideband Sagnac interferometer modulator configuration wherein the modulators are integrated as in **Figures 5a** and **5b** and the fiber directional coupler used in the architecture is a $LiNbO_3$ waveguide directional coupler integrated into the substrate.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The invention described here is a technique for generating single-sideband (SSB) modulation with suppressed carrier which utilizes traveling-wave optical modulators in a Sagnac loop. The technique descried herein circumvents the problem of complete carrier cancellation over a range of radio frequency (RF) power levels. This device serves as an enabling architecture for photonically-remoted ultrawide-band single-sideband suppressed-carrier (SSB-SC) modulated links and signal processing.

In the preferred embodiment **10**, **Figure 3a**, the wideband single-sideband modulator **10**, optical power **12** from a polarized light source (not shown) is applied via polarization-maintaining fiber (PolMF) to a 3-db directional polarization-maintaining fiber optic coupler **16**, a device well known to those skilled in the art, where it is split equally into CW-propagating and CCW-propagating lightwaves **18** and **22**, respectively, in a Sagnac loop **24**, or "loop mirror.". These lightwaves **18** and **22** are π/2 out of phase due to the action of the coupler **16** and remain so when they return to the coupler **16** because they travel equal distances around the loop **24**.

In the architecture shown in **Figure 3a**, the CW- and CCW-propagating waves **18** and **22**, respectively, are modulated equally, preferentially and respectively, by an amplitude modulator (AM) **32** and phase modulator (PM) **34**, so that the technique works over a much larger range of RF power levels. It is important to note that the AM and PM modulators (ideally) only modulate the optical carrier in one direction; that is, in **Figure 3a** the AM modulator **32** (ideally) modulates the optical signal traveling in the preferred direction (as denoted by the arrow) even though light travels through the modulator in both directions. The AM **32** and PM **34**, preferably are LiNbO3 traveling wave modulators, however, other types of modulators may be utilized. In the AM **32**, the CW-propagating optical signal **18** is intensity modulated by the radio frequency (RF) signal **28**. It should be noted that a push-pull modulation is required here in order to ensure that no unintentional phase modulation (chirp) is added to the optical carrier. This is ensured by using a push-pull electrode design as discussed above and by applying the appropriate DC bias voltage **29** to bias the modulator at quadrature. The CCW-propagating optical signal **22** is synchronized with the CW-propagating signal **18** and phase modulated by the same RF signal **28** phase shifted 90° by passing through a 90° RF phase shifter **38**, a device well known to those skilled in the art. The CW- and CCW-propagated waves **18** and **22**, respectively, are recombined in the 3-dB directional coupler **16** where the carrier components of the two optical signals **18** and **22** cancel in the transmit direction, resulting in an optical signal **36**, with the carrier suppressed, that exits through the transmitted port **36** and is applied to a using device (not shown).

As the phasor diagram of **Figure 3b** indicates, the action of the directional coupler **16** is such that the return waves from the loop **24** are combined with π relative phase shift at the transmitted port **36**. The relative phase of the inputs to the modulators **32** and **34** determined by the phase shifter **38** sets the timing of the modulation sidebands such that either the upper or lower (frequency) sidebands cancel. With this technique, carrier suppression of > 30dB is achievable because the magnitudes of the modulation phasors, indicated by the arrows **42** and **44** for the AM **32** and arrows **46** and **47** for the PM **34**,are equivalent. The modulation phasors are colinear but out of phase as a result of the type of modulation applied to each. The vector addition of the phasors in **Figure 3b** is such as to achieve a suppressed carrier single sideband signal **48**, as shown in **Figure 3c**.

With this architecture, there are two essential frequency response characteristics. First, practical modulators exhibit unintentional modulation in the non-preferred, CCW-propagating direction. This unintentionally modulated signal can reduce or enhance the desired sideband outputted from the transmitted port depending on the relative phase of the signal. Since the modulators **32** and **34** are located a distance d from the center of the loop **24**, the "non-preferred" unintentionally modulated waves from each modulator **32** and **34** arrive at the coupler **16** with phase relative to their "preferred" counterparts given by $2df/v$ (v being the in-fiber group velocity and f the modulation frequency). As a result, the power in the transmitted sidebands varies sinusoidally with frequency. The null spacing $\pi v/d$ can be increased by placing the modulators **32** and **34** as close to the loop **24** center as possible, thereby reducing variation in the single sideband modulation with frequency. Second, the direction preference of the optical modulation by each modulator **32** and **34** decreases at lower frequencies (i.e., less than traveling-wave frequencies) and the modulation is more like that of a bulk modulator. Thus at lower frequencies, the overall response decreases due to sideband as well as carrier cancellation. **Figure 4** shows the measured output of the architecture described in **Figure 3a**.

In an another preferred embodiment **20**, as shown in **Figures 5a** and **5b**, a phase modulator **34** and a "push-pull" intensity modulator **32** are combined on a single substrate **52** with their RF inputs **28** and **44** at opposite ends fed toward a common center electrode termination **46** in order to obtain a very small distance between effective modulation points-of-origin. As in **Figure 3a**, the AM **32** must be placed in quadrature using DC bias **29**. This device **42**, detailed in **Figure 5a**, is then placed at the center of the loop **24**, as shown in **Figure 5b**, to improve modulation bandwidth by reducing the delay differential between the "preferred" and "nonpreferred" modulation components of the counterpropagating waves in each modulator portion (AM **32** and PM **34**) of the monolithic dual modulator **42**.

Further, in another preferred embodiment **30**, as shown in **Figure 6**, the modulators **32** and **34** as well as the Sagnac loop **24** may be integrated onto the modulator LiNbO3 substrate **52**, reducing environmental influences on the amplitude characteristics of the loop **24**. In such a device **30**, the fiber directional coupler **16** used in the previous embodiment **20** is replaced by a $LiNbO_3$ waveguide directional coupler **54** integrated into the substrate **52**. Note that the embodiments **10**, **20**, and **30** contain the same basic architecture with increasing levels of component integration (**Figures 3a**, **3b**, and **3c**; **Figures 5a** and **5b**; and **Figure 6**).

The advantages of the wideband single-sideband modulator include those of SSB-SC transmission itself, i.e., efficient use of available spectrum and power gain. In addition, the wideband single-sideband modulator has advantages associated with optical SS techniques such as the ability to combat chromatic dispersion, the ability to remotely sense and transmit microwave signals via optical fiber, and the ability to perform signal processing functions such as RF spectrally shifting or spectrally inverting microwave signals.

The wideband single-sideband modulator surpasses other optical SSB-SC techniques in terms of its instantaneous bandwidth, degree of bias stability provided by the loop architecture, and in its operation over large power ranges.

Although this 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 these preferred embodiments without detracting from the scope and spirit of the invention.

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Serial No.

PATENT APPLICATION
Navy Case No. 79,759

ABSTRACT

The wideband single-sideband modulator generates single-sideband (SSB) modulation with suppressed carrier utilizing traveling-wave $LiNbO_3$ modulators in a Sagnac loop. In the wideband single-sideband modulator, optical light from a linearly-polarized source is injected into polarization-maintaining fiber (PolMF) where it is split equally via a polarization-maintaining (PolM) directional fiber coupler, resulting in counterpropagating lightwaves in a Sagnac loop. These counterpropagating waves are $\pi/2$ out of phase due to the action of the coupler and remain so when they return to the coupler because they travel equal distances around the loop. Because the coupler is a reciprocal device, if the waves return to the coupler with equal amplitudes, they will recombine and exit the original port toward the polarized light source. The technique achieves true carrier cancellation over a range of radio frequency (RF) power levels, thereby serving as an enabling architecture for photonically-remoted ultrawide-band single-sideband suppressed-carrier (SSB-SC) modulated links.

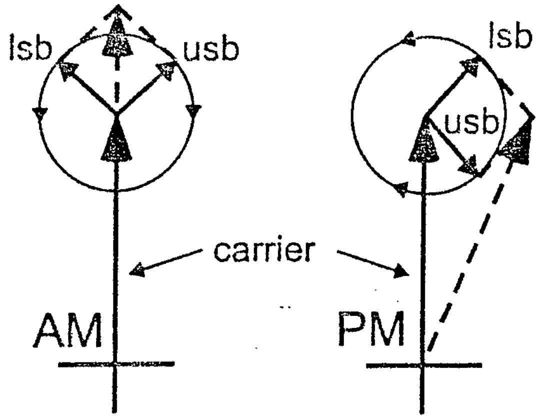


Figure 1b

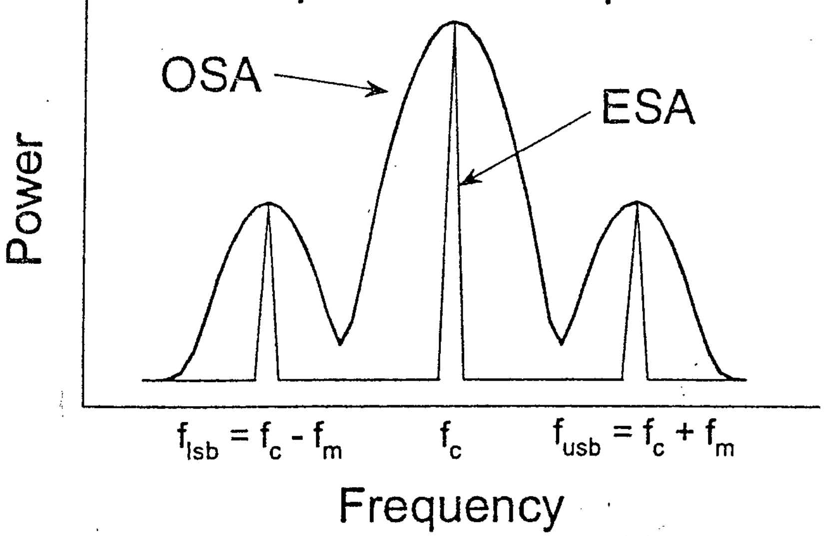


FIGURE 1a

Figure 2a

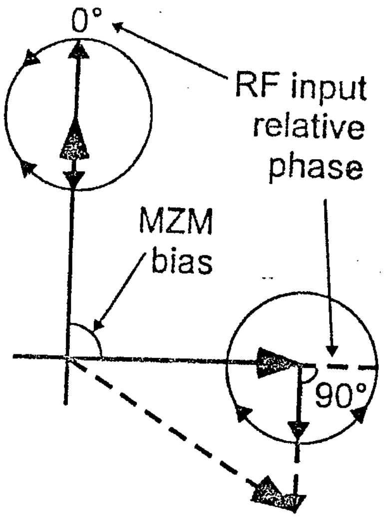
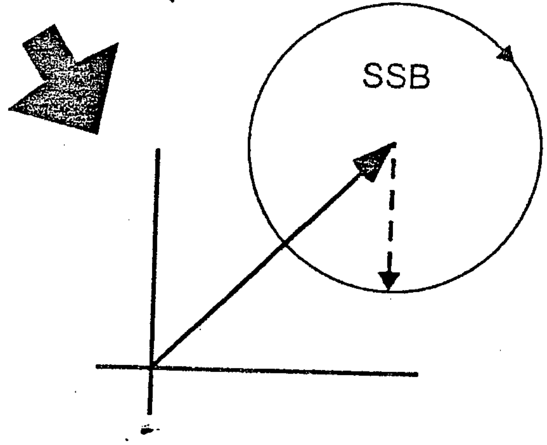


Figure 2b



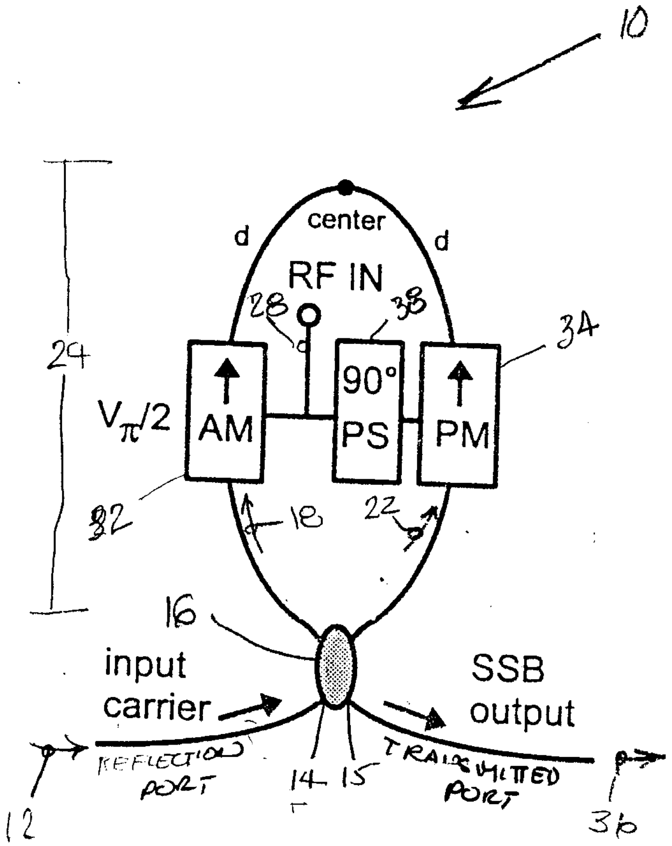


Figure 3a

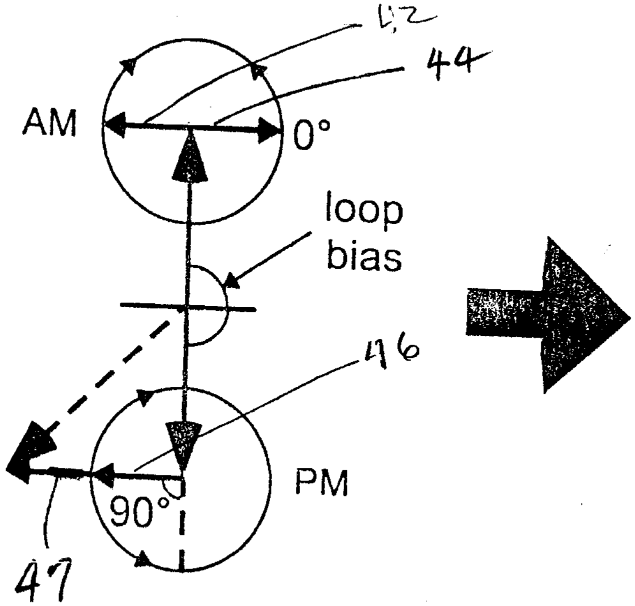


Figure 3b

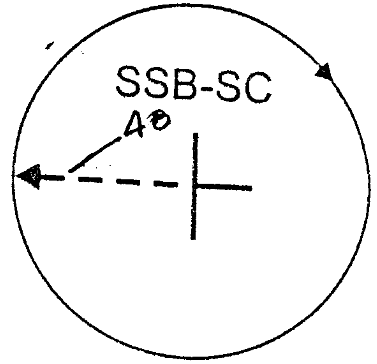


Figure 3c

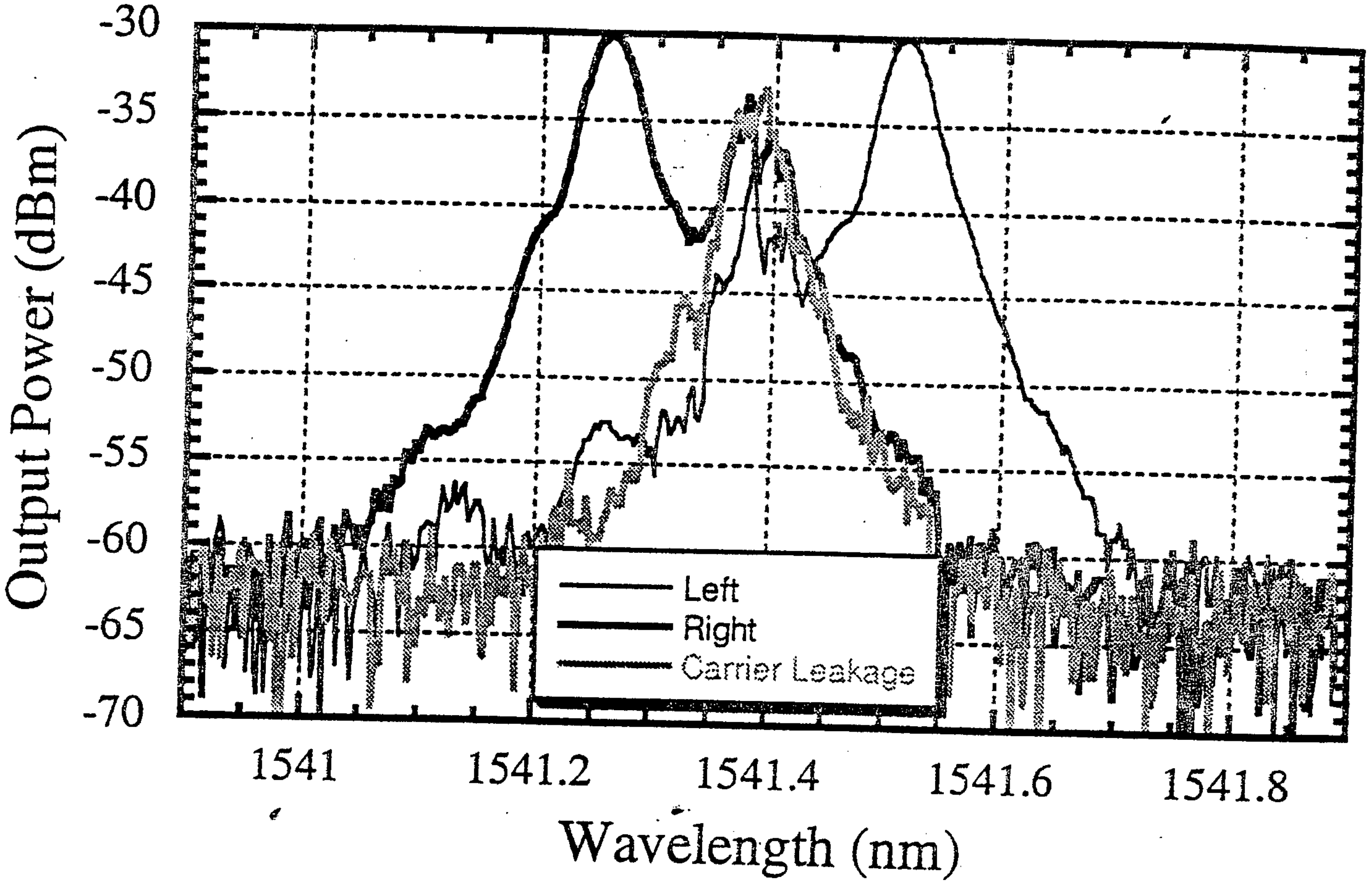

-30
-35
-40
-45
-50
-55
-60
-65
-70
Output Power (dBm)
1541
1541.2
1541.4
1541.6
1541.8
Wavelength (nm)
Left
Right
Carrier Leakage

Figure 4

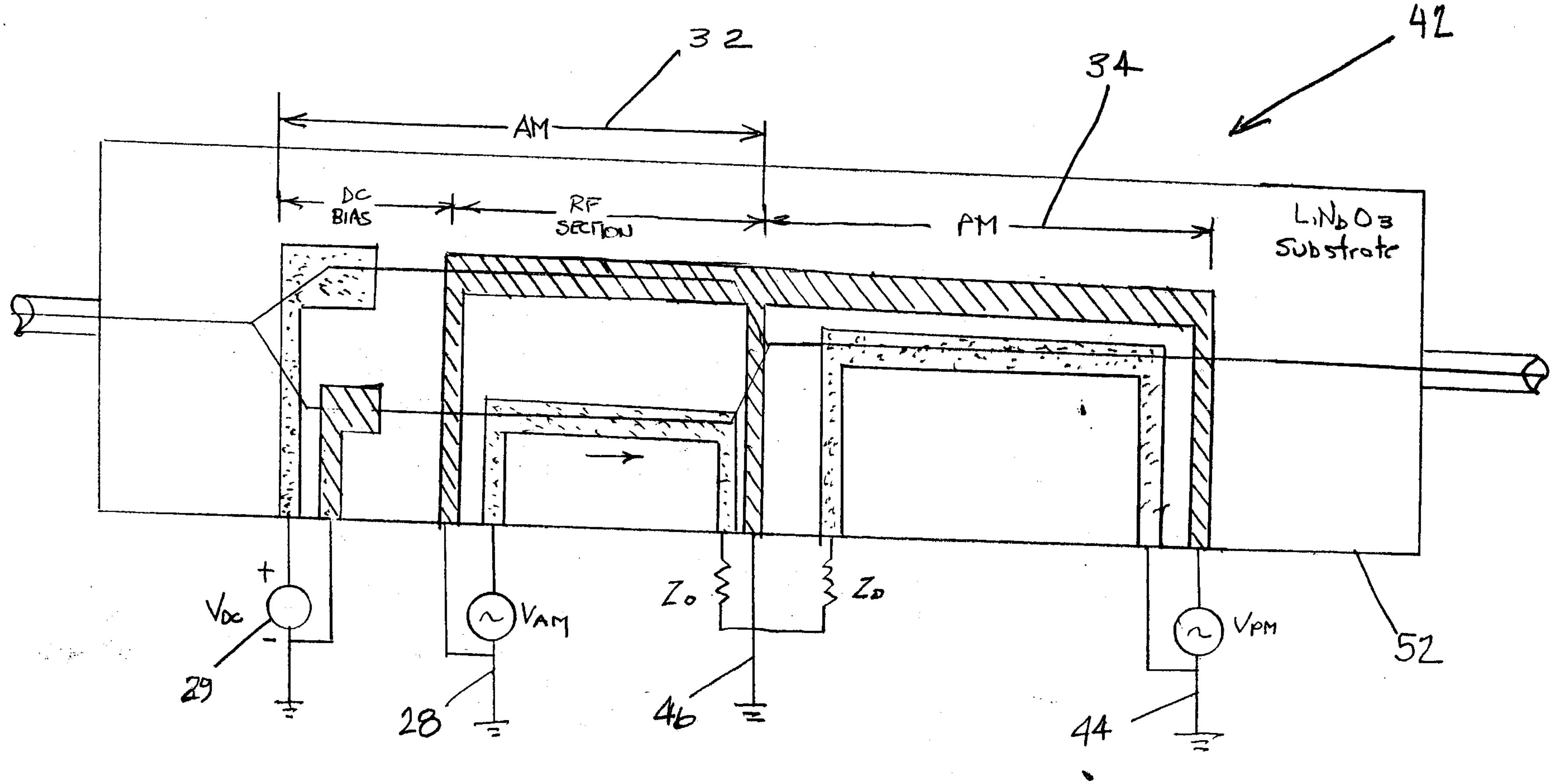

42
32
34
AM
DC BIAS
RF SECTION
PM
LiNbO3 Substrate
+
-
V_{DC}
29
V_{AM}
28
Z_0
Z_0
46
V_{PM}
44
52

Figure 5a

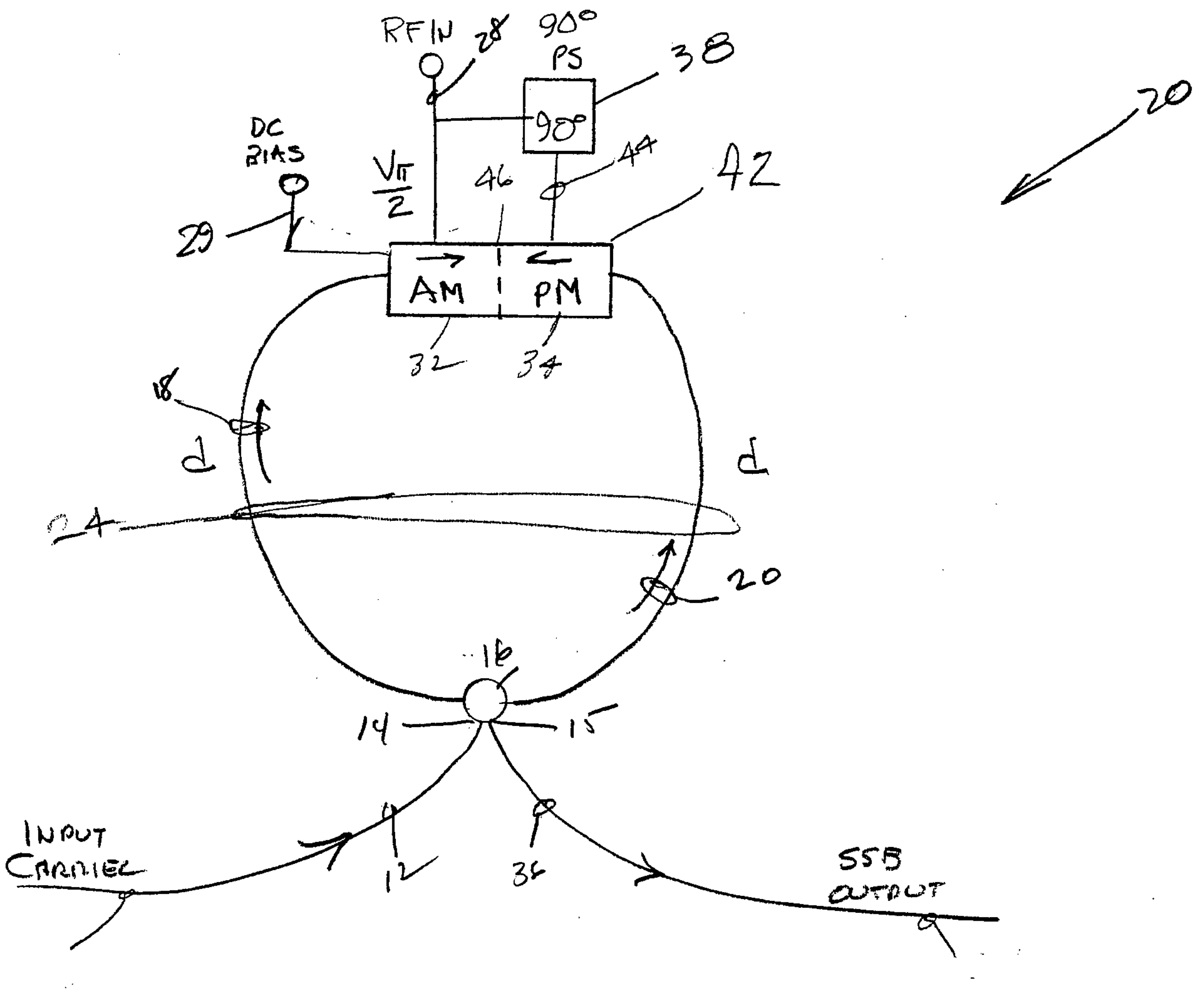

RFIN
28
90°
PS
38
90°
20
DC
BIAS
29
$\frac{V_\pi}{2}$
46
44
42
AM
PM
32
34
18
d
d
24
20
16
14
15
INPUT
CARRIER
12
36
SSB
OUTPUT

Figure 5b

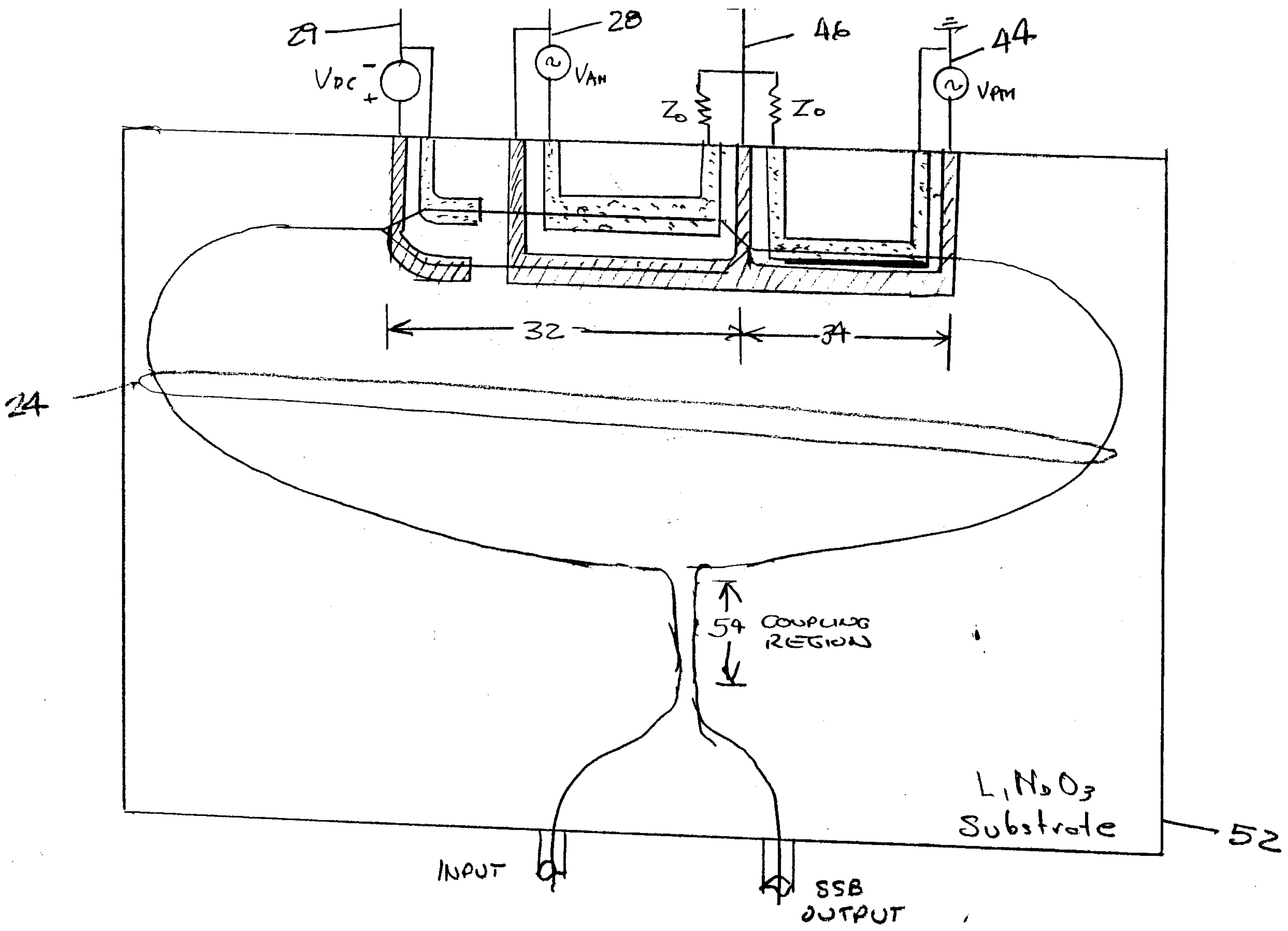

29
28
46
44
V_{DC} - +
V_{AM}
Z_0
Z_0
V_{PM}
32
34
24
54
COUPLING REGION
$LiNbO_3$ Substrate
52
INPUT
SSB OUTPUT

Figure 6