A New OEO Design
Using Optical Phase Modulation and Modulation Suppression

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Abstract—We present the design for a phase-modulated Opto-Electronic Oscillator (OEO) that incorporates asymmetric Mach-Zehnder (AMZ) interferometers as phase demodulators together with PM modulation suppression. The new design promises to obtain in the electro-optical domain the low-noise advantages previously achieved in RF and microwave oscillators by the use of carrier suppression but which have been achieved only to a limited extent in OEO's.

I. INTRODUCTION

OEO designs using RF carrier suppression have already been demonstrated[1], and they do show the rejection of amplifier flicker noise as is shown in microwave oscillator and interferometer applications [2]. However, a second important advantage of microwave carrier suppression, the reduction of the effects of thermal- or shot-noise [3], has not been realized in an OEO application before now. This second reduction is made possible in microwave applications by the use of higher power levels in the oscillator or interferometer than can be tolerated by a low-noise follower amplifier, combined with a means for reducing the power at the detector that still preserves the systems sensitivity i.e. without reducing the output response to phase variation induced by the resonator discriminator or component under test.

The design presented here realizes this second advantage for the first time in the opto-electronic arena by enabling the effective use of high optical power levels to reduce shot-noise induced frequency variation in an OEO. This is done by use of an Asymmetric Mach-Zehnder (AMZ) phase demodulator (phase detector) with unbalanced outputs together with modulation suppression. With appropriate delays and phases, the AMZ demodulator can transmit virtually all of the optical power to a terminated output port while a signal with suppressed optical carrier but with high sensitivity to input PM is developed at the other port. Sideband amplitude also is reduced before detection by use of a phase un-modulator (matched to a PM modulator that replaces the AM unit used in a typical OEO). This reduction of both carrier and sidebands combines to prevent overload of the low-noise optical detector (which always has a low optical saturation power) as optical power is increased.

II. OEO DESIGN WITH PM MODULATION SUPPRESSION

Figure 1 shows an overall block diagram for the OEO design. It consists of two parts which are separated by dashed containing boxes. The left box contains a completely self-contained phase-modulated OEO with an available electrical tuning signal input. It consists of a low-noise CW laser, microwave phase modulator, delay line, phase detector (AMZ Phase Demodulator), mode selection filter, electrically variable phase shifter, and a power amplifier to drive the modulator.

The OEO in the left (dashed) box in Figure 1 operates in a manner identical to that of conventional OEOs: Identical, that is, except for the use of phase modulation (a PMOEO) instead of amplitude modulation, and except for the use of a high-powered laser, so that only a fraction of the power need be tapped for use by the oscillator itself. The right half of Figure 1 shows the added modulation-suppressed noise reduction system that senses and corrects for frequency noise in the PM OEO on the left. The use of added noise reduction stages to OEO oscillators is also similar to previous designs [1] which have used stages with carrier-suppressed RF electronics to reduce the noise contributions of RF components in an active OEO oscillator. These added stages work by sensing the frequency error with lower noise than is practical in an active oscillator, and then undo the effects of that noise with feedback. The present unit also works in this way.

However, instead of improving only the performance of RF components, the present noise reduction system also reduces noise inherent in the optical detector itself. The scheme improves performance in two ways; first by enabling the use of very high optical power levels to reduce thermal- and photon shot-noise contributions to the system frequency fluctuations; and secondly by allowing larger modulation levels than would otherwise be possible. Part of the solution is in the AMZ phase demodulators, which will be discussed in the next section and which can be arranged to provide a reduced signal to a low-noise optical detector (thus preventing overloading) while still preserving a high sensitivity to phase modulations on the optical signal. However, what must be measured is the variation of the phase of the phase modulation that is applied to the optical signal, and not the modulation itself, which would overload the detector. So, to enable a high sensitivity with the
Fig. 1. Schematic diagram of the Modulation-Suppressed OEO (MSOEO) consisting of a tunable phase-modulated OEO on the left and a modulation-suppressed noise-reduction subsystem on the right.

As shown in Figure 1, the signal from this small, nominally zero, remnant modulation is amplified and filtered and then mixed with a reference RF signal from the OEO (via $\Phi_3$) to generate two feedback signals; one that matches the magnitude of the un-modulation signal to the PM modulation, and the primary feedback signal, that corrects the phase fluctuations of the OEO by modifying its operating frequency via phase shifter $\Phi_2$.

Fig. 2 shows the same schematic plus details of the AMZ demodulator in the PMOEO module on the left. This demodulator is designed to operate with input signals nominally equal to that required by optical detectors, i.e. without optical carrier suppression, as discussed in the next section.

III. AMZ DEMODULATOR WITH BALANCED OUTPUT

Figure 3 shows the Asymmetric Mach-Zehnder interferometer-based demodulator from Figure 2. This AMZ demodulator converts a phase modulated optical input into amplitude modulated signals at its outputs by means of a $\lambda_{rf}/2$ (or an odd multiple thereof) difference in the optical lengths of the two branches (where $\lambda_{rf}$ is the RF wavelength). This length difference, typically a centimeter or so for X-band microwave frequencies ($\sim 10$ GHz), causes the phase modulations at the ends of the two arms to be inverted in phase with respect to each other. As described in the following, if the optical phases are appropriately adjusted this gives rise to signals at the two outputs that have equal amplitudes and inverted AM optical signals that are proportional to the initial PM at the optical input. When the output optical signals are detected, electrical signals are generated with equal DC levels and inverted RF signals. The RF and DC signals are separated with bias tees, with RF signals combined into a common output while a differenced DC signal is used to adjust the optical phase in the interferometer to preserve output balance.

For a signal to be developed at the AMZ demodulator output the optical signal from the laser must have a coherence length that is greater than the length difference between the two arms. Since the length difference is only a cm or so and since coherence lengths for high-quality lasers are typically meters to hundreds of meters, this requirement is easily met.

As shown in Figure 4, the input to the interferometer at the heart of the AMZ demodulator is split into two unequal arms in an upper hybrid, a $\lambda_{rf}/2$ length difference inverts the
Fig. 2. Diagram of the MSOE with an expanded view of the AMZ phase demodulator in the tuneable PM OEO subsystem.

Fig. 3. Phase modulation at the input to the Mach-Zehnder interferometer can be represented by Phasors for the carrier, and for upper and lower sidebands. Higher sidebands also contribute, giving the curved oscillatory path for the phasor as shown by the double arrow.

Fig. 4. Added length of the right arm of the interferometer gives a 180 degree phase shift between the phase modulations in the two arms before they are re-combined at the output.

sense of the phase modulation of the right (red) signals with respect to those on the left (green). When combined with a $\pi/2$ phase difference between the optical phases (represented here by the 90 degree angular rotation between red and green signal phasors in Fig. 5) the phase modulation at the input is converted into amplitude modulation at the output of the lower hybrid (blue and orange phasors).

If the optical phase, as adjusted by the optical phase shifter, $\delta\Phi$ in Figure 6, is not correctly adjusted the RF amplitudes at the two outputs are unbalanced and the DC levels are also unequal. This is indicated by the graph in the inset which shows the (RF) time evolution of the voltage two outputs together with DC levels (dashed lines). As shown in Figure 7, the difference between these voltages is applied to an
Phase-Modulated Optical Input

Photo-diodes

δΦ

Time

Diode Voltage

Antisymmetrical Rotations of Signal Phasors Combine to give Amplitude-Modulated Outputs

Optical Phase Error Gives Assymetrical RF Outputs and a DC Offset

Phase-Modulated Optical Input

Microwave Outputs

Photo-diodes

Fig. 5. “Out-of-phase” optical phase modulations in the left and right branches of the interferometer combine to give amplitude modulated signals at its outputs. Detector outputs also show a 180 degree phase difference, as shown in the graph inset.

Fig. 6. Improper adjustment of the optical phase delay in the right arm rotates its output phasor, giving rise to unbalanced RF outputs and a DC offset between them as shown in the graph inset.

integrating amplifier in a control loop to continuously adjust the optical phase and so to preserve the π/2 optical phase difference between the two arms.

IV. AMZ DEMODULATOR WITH UNBALANCED OUTPUTS

Figure 8 shows the overall schematic diagram for the PMOEO with details filled in for the AMZ demodulator in the noise reduction subsystem. Where the AMZ demodulator previously described in the PMOEO receives only a small fraction of the optical power in order not to overload its optical detectors, the full optical power is applied (after passing through the PM un-modulator) to the demodulator on the right.

This second AMZ demodulator operates in a manner similar to the one used in the PMOEO, except that the optical phase is adjusted so that one of the outputs is much smaller than the other. For this case, virtually all of the signal power from a small input phase modulation appears at the low-power (dark) port while all of the optical power appears at the other (bright) port. The bright port is terminated to absorb the optical power without unwanted reflections, while the signal at the dark port is optically detected and then (as in the balanced AMZ demodulator described above) split into a baseband signal that is used to control the optical phase in the interferometer, and an RF signal that is sent on to the quadrature RF detector.

This configuration (modulation suppression plus unbalanced AMZ demodulator) allows the use of high optical power levels without overloading the optical detector in the demodulator and also gives increased sensitivity to phase variations in the optical PM signal from the delay line due to the use of higher optical power and the high sensitivity at the dark port of the unbalanced AMZ demodulator.

As shown in Figure 9, this AMZ demodulator is adjusted with optical phase to give unbalanced outputs, a bright port labeled B and a dark port D which presents an optical signal with amplitude that is very sensitive to any input phase modulation. Because this modulation is always nominally zero due to the feedback discussed in the first section, only a very small optical carrier is required at the dark port. The DC bias at the output of the photo-diode detector reflects this carrier level, and is compared with a baseband signal level and integrated to keep the optical phase at a proper value.

Fig. 7 also shows how the optical phase δΦ can be adjusted to provide a small signal with large amplitude modulation at a dark port. Time dependence of the signal amplitudes is shown in the inset graphs which show the variation at the RF modulation frequency together with DC level values.
As in the previous phasor diagrams, the angular oscillations (at the RF frequency) of the red and green phasors in Figure 9 are 180 degrees out of phase due to the $\lambda_{rf}/2$ difference in the lengths of the arms in the interferometer. That is, as the red phasor rotates to the left, the green one rotates to the right, and vice versa. As indicated in the diagrams, the output port phasors are the vector sums of the input phasors with appropriate (quadrature) phase shifts. By proper adjustment of the optical phase $\delta \Phi$ the bright port sum phasor (yellow) is shown to have a large length but a small variation due to oscillation of the input phases, while the dark port output phasor (blue) shows a smaller value but a much larger oscillation. These are represented in the time variation shown in the inset graph, where the average values are also shown as dashed lines.
The magnitudes of the phase oscillations are shown much enhanced in Figure 9. Due to the effect of modulation suppression, only a remnant noise phase modulation (at the RF frequency) would remain at the input to the unbalanced AMZ demodulator. This allows the use of a very small remnant carrier in the dark port and thus an input power that is very much larger than that which the photo-diode detector, as shown in Figure 10, can withstand.

Figures 11 and 12 show how errors in the amplitude and phase of the un-modulating signal are detected and corrected. For the case of amplitude error as shown in Fig. 11, the resulting (small) phase modulation is approximately in phase with the applied modulation signal and is detected and corrected with an integrator through the “Y” port of the X–Y mixer. On the other hand, if phase shifter $\Phi_2$ is adjusted as illustrated in Fig. 12 (or if the PM OEO fluctuates from the proper frequency) the consequent phase error is corrected by tuning the frequency of the PM OEO, thus reducing its frequency fluctuations while also providing a means for tuning the frequency of the combined oscillator.

V. CONCLUSIONS

Designs have been developed and presented for a new phase–modulated optoelectronic oscillator with a modulation–suppressed noise reduction subsystem, and for optical phase demodulators that enable advantageous application of high optical powers without overloading the optical detectors. The use of modulation suppression allows a reduction for the first time in an OEO for shot noise at the detectors; taking advantage of higher available optical power and larger phase modulation amplitude.

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REFERENCES

