Opto-Electronic Oscillator With Quality Multiplier

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Opto-Electronic Oscillator With Quality Multiplier

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***Abstract*—This paper presents an opto-electronic oscillator (OEO) with a regenerative electronic circuit that increases the selectivity of the oscillator's loop. The regenerative circuit works as a multiplier of the bandpass filter's quality factor. This makes it possible to realize very narrow bandwidths and thus increase the side-mode suppression ratio of the OEO. Our measurements show an almost 20-dB increase in the suppression of the side modes at the expense of an increase in the phase noise by approximately 4 dB at a 1-kHz frequency offset.**

***Index Terms*—Feedback, opto-electronic oscillator (OEO), phase noise, q-multiplier, quality factor, regenerative circuit, short-term stability, side mode, suppression.**

I. Introduction

THE opto-electronic oscillator (OEO) is a well-known solution for generating high-frequency signals with low phase noise, first described by Yao and Maleki in 1995 [1]. Since the invention, an extensive research has been carried out by different researchers [2]. The main design issues are improving the long-term stability [3], [4], reducing the power of the side modes [5]–[12], reducing the number of electrical components [13]–[17], and optimizing the phase-noise performance [18]–[20].

In this paper we focus on how to increase the side-mode suppression ratio (SMSR). We propose a method in which an additional electrical circuit is used to decrease the bandwidth of the bandpass filter used in the OEO's loop. The reason for adding an electrical circuit to the filter is because of the physical limitations when designing very narrow bandpass filters. Different authors have already suggested a number of solutions for overcoming the filter's bandwidth problem. In addition to an increase in the SMSR, the effect of a particular method on the phase noise is also important.

To increase the SMSR of an OEO the addition of a second optical path is suggested in [5]–[7]. A more than 30-dB improvement in the SMSR is reported in [5] because of the dual-loop configuration. In [6], the authors used an optical-only dual-loop configuration and achieved a 60-dB increase in the SMSR. An additional loop-gain control was suggested in [7] for an OEO with an optical-only dual loop to provide an additional 20-dB increase in the SMSR.

The use of a dual-injection-locked opto-electronic oscillator (DIL OEO) was also suggested as a way of increasing the SMSR [8], [9]. An SMSR higher than 140 dB is reported in [8], while in [9] an SMSR of approximately 130 dB is reported.

In [10], we described a method where additional phase modulation of the OEO's loop was used to increase the SMSR. A 5-dB improvement was achieved. In [11], the authors achieved a 40-dB increase in the SMSR for a coupled OEO with the use of an RF interferometer. The authors of [12] used an ultra-high finesse etalon as a photonic filter. With its bandwidth of 15 kHz they managed to suppress the side modes below the phase noise for a 10-GHz carrier signal.

To increase the SMSR in a single-loop OEO we herein propose a microwave bandpass filter with a quality multiplier (FQM). In contrast to our previously proposed method with additional phase modulation [10], where suppression ratio is increased with the usage of extracted side modes, quality multiplier (QM) increases SMSR with a decreased loop bandwidth.

The QM was introduced after the invention of a regenerative receiver. It is not clear who was the first to invent the regenerative circuit, but it is usually attributed to Armstrong [21]. The QM is a positive feedback loop that increases the selectivity and the gain of a related circuit [22]. If the QM is added to a bandpass filter, both its bandwidth and the insertion loss decrease.

We used a single-loop OEO for reasons of simplicity, performance, and the fact that the number of components is reduced to a minimum. A dual-loop OEO uses two optical delay lines and a DIL OEO uses at least twice as many components as a single-loop OEO. Some authors have also reported stability problems with injection locking [8], and it has also been reported that a short loop in the dual-loop OEO increases the phase noise compared to a long loop [5].

Despite the fact that some authors suggest replacing an electronic amplifier with an optical one [13], or with an optical link with gain [14], we decided to use microwave amplifiers in our experiment to introduce a further simplification and a reduction in the cost. To avoid electrical amplifiers, a class-E analog fiber-optic link was also proposed for an OEO, and an SMSR of 62 dB was achieved for carrier frequencies around 70 MHz [15].

An all-electronic solution for additional side-mode suppression is suggested because of the easily obtainable electrical components. Optical components, such as optical filters, are very specialized and not widely available. Such an example is the already-mentioned ultra-high finesse Fabry–Perot etalon [12].

Another reason for an all-electronic solution is the performance of the optical filters. For example, the open-loop band-

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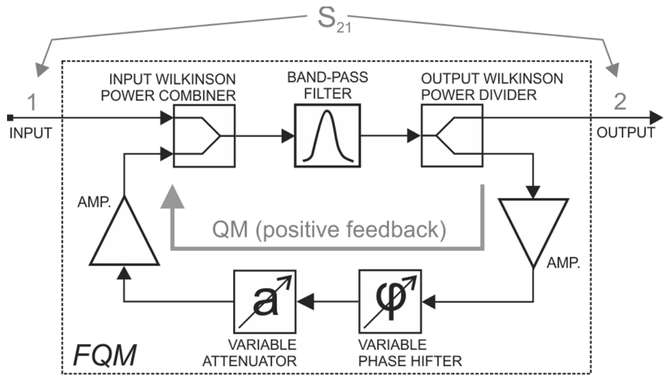

Fig. 1. Schematic diagram of a FQM, custom built in our laboratory and used in the experiments. Two microwave amplifiers, a variable phase shifter and a variable attenuator represent the QM and the positive feedback to a bandpass filter.

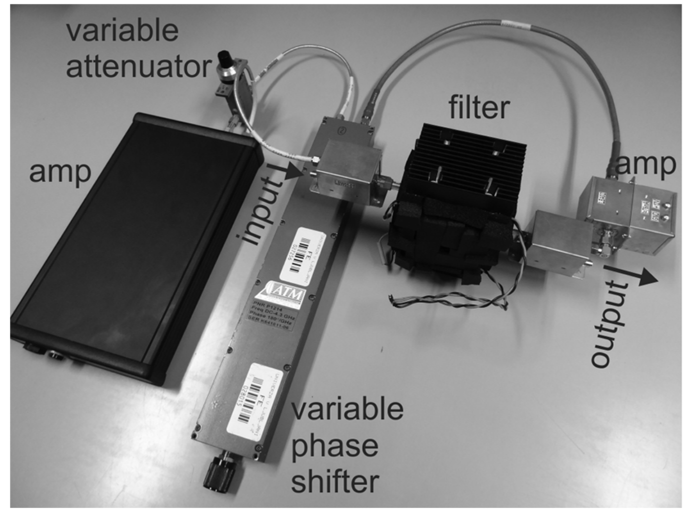

Fig. 2. Photograph of the constructed FQM. The bandpass filter is enclosed in a thermally nonconductive foam with an attached thermo-electric cooler and thermistor. This explains the electric wires, which are seen coming out of the filter. This feature of the bandpass filter was not used in the experiments, as explained in this paper.

width of an OEO with a photonic filter based on phase-modulation to intensity-modulation conversion using a phase-shifted fiber Bragg grating was reported to be around 20 MHz [16]. An SMSR of 95 dB was achieved for a free spectral range (FSR) of 400 kHz. However, this was not sufficient for our research.

The trend for replacing electrical components with optical ones can be seen in the literature. Such an example is an OEO with a resonant tunneling diode oscillator that is integrated with a photodetector [17]. The authors achieved an SMSR of 36 dB. The operating frequency was 1.4 GHz and the FSR was 154 kHz. Despite a major reduction in the size and the number of components, the SMSR performance of this solution cannot be compared to a dual-loop OEO or a DIL OEO, as previously mentioned.

In Section II, we explain the basic structure of an FQM. The experimental OEO's structure and the tuning of an OEO with a FQM are explained in Section III. In the same section, phase-noise measurements are also presented. In Section IV, the results from our experiments are compared to different known methods, which were already briefly described in this section.

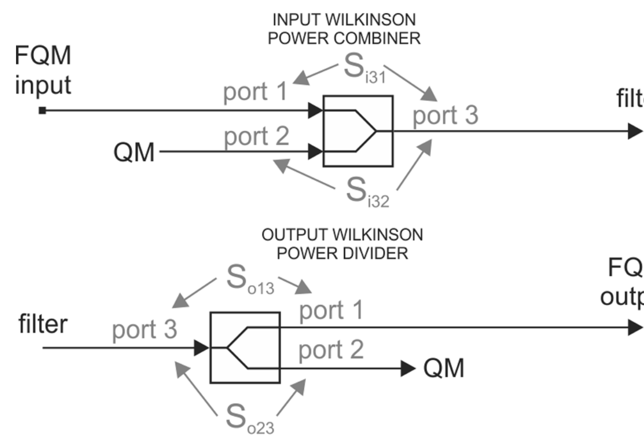

Fig. 3. Detailed explanation of the transmission coefficients of an input-power combiner and an output-power divider used in an experimental FQM.

II. QM

Our experimental FQM is shown in Fig. 1, and in Fig. 2 there is a photograph. Two microwave amplifiers, a variable attenuator and a variable phase shifter represent the QM and the positive feedback. A Wilkinson power combiner and divider are used for dividing a portion of the FQM's output signal to the QM and combining the QM's output signal with the FQM's input signal. The variable attenuator and the variable phase shifter are used to tune the FQM.

The transmission parameter S_{21} of the FQM from Fig. 1 can be described with (1). S_{r21} in (1) represents the transmission coefficient of the bandpass filter alone at its central frequency ω_0. S_{i31} is a transmission coefficient of the input Wilkinson combiner from the FQM's input port to the input of a bandpass filter. A detailed explanation of the transmission coefficients is presented in Fig. 3. S_{o13} is a transmission coefficient of the output Wilkinson divider from the output of the filter to the FQM's output. Q_L represents the filter's loaded quality factor and M is the FQM's multiplication factor. The factor M can be expressed with (2). In (2), S_{i32} and S_{o23} represent the transmission coefficients of the Wilkinson dividers, where port 2 is the port that is connected to the QM in both cases, as shown in Fig. 3. S_{f21} is a combined transmission coefficient of the QM,

$$S_{21}(\Delta\omega) = \frac{M S_{i31} S_{o13} S_{r21}(\omega_0)}{1 + jMQ_L \frac{\Delta\omega}{\omega_0}} \tag{1}$$

$$M = \frac{1}{1 - S_{i32} S_{o23} S_{f21} S_{r21}(\omega_0)}. \tag{2}$$

From (1) it is clear that the loaded quality factor of the bandpass filter Q_L is multiplied by the factor M. Additionally, the combined transmission coefficient of the filter and both the Wilkinson power dividers are also multiplied by M. In our experimental case the factor M from (2) depends only on the transmission coefficient of QM S_{f21}. S_{i31}, S_{o23}, and S_{r21} have constant values. The factor M depends only on the QM gain if the FQM's loop phase equals a multiple of 2π at the bandpass filter's central frequency. In this case the FQM has an optimum response. The latter was achieved with a variable phase shifter in the QM.

For the purposes of the experimental measurements, an FQM, the configuration of which is shown in Fig. 1, was built

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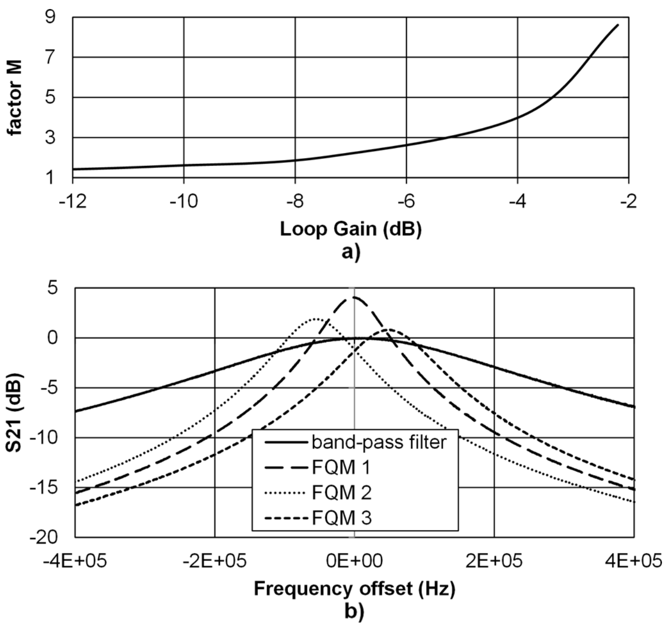

Fig. 4. Measurements of the custom-built FQM. (a) Dependence of the multiplication factor M on the loop gain. (b) Comparison of the bandpass filter's bandwidth with the FQM bandwidth (*FQM 1*). The bandwidth of the FQM is nine times narrower (40 kHz instead of 360 kHz). The curves *FQM 2* and *FQM 3* represent the frequency response when the FQM is not in the optimum regime.

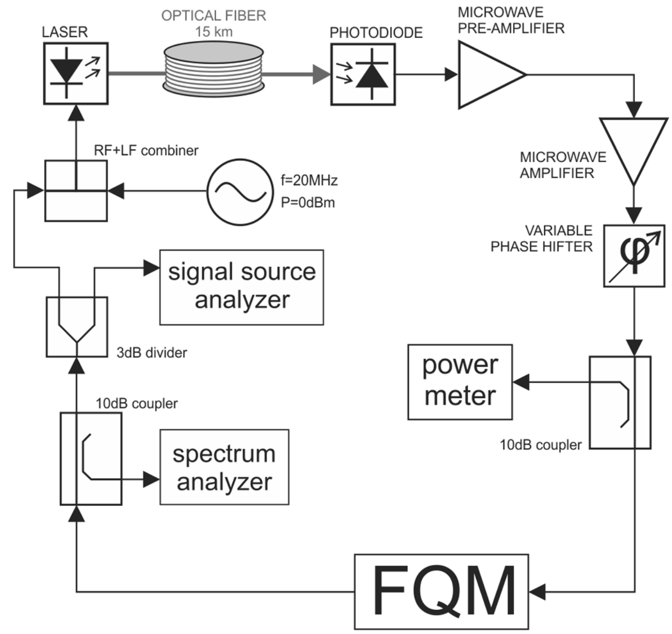

Fig. 5. Experimental OEO with the implemented FQM.

in our laboratory. A photograph is shown in Fig. 2. A dielectric loaded cavity resonator was used for the bandpass filter with a bandwidth of 360 kHz and a 10-dB insertion loss. The cavity's Q-factor was approximately 8300 at 3 GHz, which was also the frequency of the operation. We used two commercial amplifiers in a feedback loop. The first (a low-noise pseudomorphic HEMT (pHEMT) amplifier) had a saturation power of 20 dBm and gain of 8 dB. The saturation power of the second one (a pHEMT power amplifier) was 31 dBm and the gain was 11 dB. All these values were measured.

A continuously variable attenuator was required to change the gain of the QM and, therefore, the factor M. If the attenuator was adjusted below a certain value of the attenuation, the FQM started to oscillate. In this case the gain of the FQM's loop was greater than 1. This had to be avoided for the proper operation of our constructed FQM.

The FQM shown in Fig. 1 was measured with a network analyzer. The factor M of the FQM was measured as a function of the FQM's loop gain and is shown in Fig. 4(a). It is clear that the factor M increases with the loop gain.

Fig. 4(b) shows the FQM's transmission coefficient S_{21} when the factor M equals 9 and for three different settings of the variable phase shifter in the QM. The bandpass filter alone is shown with a solid line. The vertical axis in Fig. 4(b) is normalized to a bandpass-filter insertion loss. The curve *FQM 1* shows the FQM's S_{21} when the FQM has an optimum response. It is shown that the QM reduces the insertion loss by 4 dB. In this case the Q-factor increases to 75 000. The filter's bandwidth of 360 kHz is reduced to 40 kHz. The curves *FQM 2* and *FQM 3* represent S_{21} when the FQM's loop phase is $\pi/60$ of the optimum response.

An undesirable side effect of a QM is the increase in the electronic noise temperature. The effects of the quality increase and the noise increase cancel out in Lesson's equation [23], making a QM useless in an all-electronic oscillator. The electronic noise temperature is intrinsically much higher in an OEO due to the noisy electrooptical delay line. In the latter case, a QM adds a small amount of electronic noise, compared to a delay line, therefore making the use of a QM the rational choice.

The FQM's noise figure also increases with the factor M. If the loop gain is increased from -12 to -2 dB, the M factor is multiplied by almost 9, as shown in Fig. 4(a). For the same loop-gain range, a 3-dB increase in the noise figure was measured for the FQM. The flicker noise was not measured. The authors of [24] report that the flicker noise of the regenerative amplifier increases with the gain of the feedback loop. Since the FQM can be considered as a regenerative amplifier, we therefore assume that the higher the multiplication factor, the higher the flicker noise.

III. Experimental OEO

In our experimental configuration the FQM from Fig. 2 was implemented in a 3-GHz OEO with 15 km of G.652D single-mode optical fiber, shown in Fig. 5. A photograph of the constructed OEO is shown in Fig. 6. The FSR of the constructed OEO was 12.4 kHz. We are aware that at 3 GHz the OEO does not exhibit superior performance compared to well-known solutions such as a quartz oscillator with a multiplier.

With a quartz-crystal oscillator at 100 MHz it is possible to achieve a phase noise of -140 dBc/Hz at a 100-Hz frequency offset [25]. If this is multiplied to a frequency of 3 GHz, the phase noise increases by approximately 30 dB, as a result of the multiplication. At a 100-Hz offset the phase noise of the 3-GHz signal is then -110 dBc/Hz. As is seen latter in this section, this is better than our oscillator. The 3-GHz frequency was chosen because of the measurement equipment's limitations and because of the availability of the hardware in our laboratory. In addition, we believe it is more practical to develop a concept at lower frequencies. Another important factor that led us to this

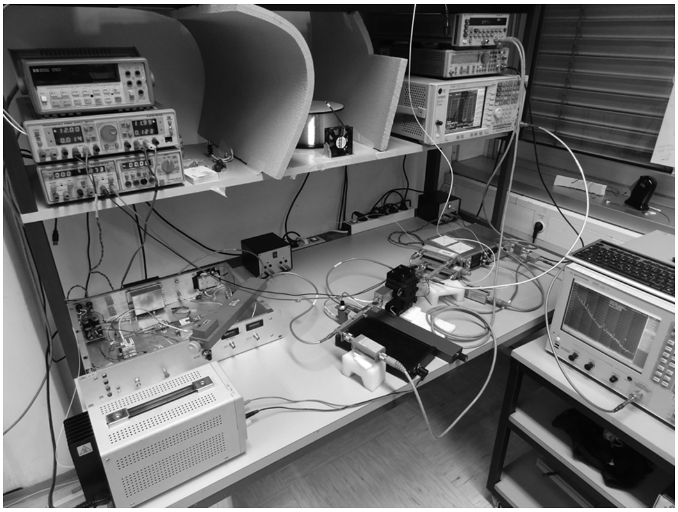

Fig. 6. Photograph of the measurement setup and the constructed OEO with FQM. It is possible to observe that an isolator is added before the FQM and a variable attenuator after the FQM. These two elements do not affect the performance of the OEO, which is presented in this paper, and are therefore not necessary. The reason for additional elements is that exactly the same setup was used for a number of measurements.

decision was the independence of the OEO phase noise from the operating frequency [1].

Directly modulated, a semiconductor distributed-feedback laser with a wavelength of 1550 nm was used as the optical source and an InGaAs p-i-n photodiode was used for the signal detection. For the photodiode signal's pre-amplification, a commercial single bipolar junction transistor in class A was used. A commercial monolithic microwave integrated circuit (MMIC) was used for the additional amplification.

In [18] it was shown that the phase noise of an OEO is a result of the Brillouin and Rayleigh scattering, among other reasons, such as the laser's relative intensity noise and the photodetector's flicker noise [19]. The authors of [18] suggested using an additional laser-frequency modulation. In [20], guided-entropy-mode Rayleigh scattering (GEMRS) was investigated as a source of noise in an analog optical transmission line. Phase modulation was suggested to decrease this type of noise.

In our experiment, the laser diode was additionally intensity modulated as this was the only way to modulate a commercial laser module. Due to the direct laser modulation, its frequency was modulated as a side effect. An additional 0-dBm 20-MHz modulation signal was chosen by experimentation. We found that frequencies higher than 20 MHz and powers lower than 0 dBm do not decrease the phase noise as well as the lower frequencies, such as 20 MHz and powers higher than 0 dBm. There was also no noticeable decrease in the phase noise for frequencies below 20 MHz or power levels above 0 dBm compared to a 20-MHz and 0-dBm modulation signal. Therefore, we chose the highest frequency and the lowest power.

An additional modulation signal was led to the laser's input through a combiner of high- and low-frequency signals, which was custom made in our laboratory. The estimated noise figure of our electrooptical delay line is around 40 dB, with all our noise-reduction countermeasures in place.

For the phase-noise measurement, the signal source analyzer with a two-channel cross-correlation was used. It was connected to the 3-dB power divider located before the laser's modulation input. For monitoring the signal spectrum and the FQM's output power, a spectrum analyzer was used, connected to a 10-dB coupler. Before the FQM in the OEO's loop, another 10-dB coupler was used to measure the FQM's input power with a power probe. The measurement equipment is shown in Fig. 6.

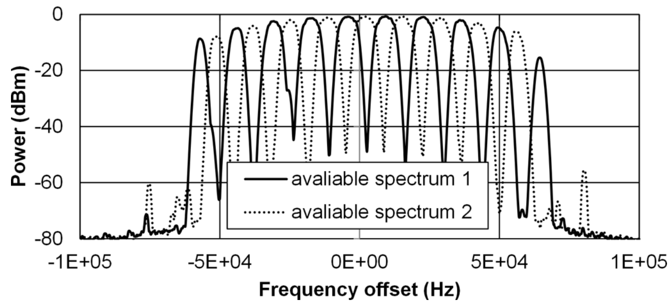

Fig. 7. Available spectra for two different settings of the phase shifter in the OEO's loop. The difference between the curves *available spectrum 1* and *available spectrum 2* is in a phase change π in the OEO's main loop.

Our experimental OEO from Fig. 5 is similar to the self-injection-locked oscillator presented in [26]. The electrical cavity oscillator in [26] has an almost identical structure to our FQM. The main difference is that the FQM has a loop gain, which is lower than 1 and therefore does not oscillate. The oscillation is provided by the electrooptical loop. In [26] the oscillation is provided by the electrical cavity oscillator, and injection locking with an electrooptical loop is used to lower its phase noise.

A. FQM Tuning

When the FQM is inserted into the OEO, the OEO's loop impedances affect the FQM's properties compared to the matched impedances of the network analyzer. Therefore, the FQM has to be tuned when already implemented into an OEO.

There are two mechanisms for adjusting the frequency in an OEO with an implemented FQM. One is to change the oscillator's loop delay time. In our experimental case, this was achieved with a variable phase shifter, located in the oscillator's loop, as shown in Fig. 5. The second mechanism is to vary the QM's phase in the FQM itself.

By changing the loop delay time, it is possible to achieve a continuous change of the frequency. When the phase in the QM is altered, the frequency change is not continuous. There are regions where the oscillation stops. This is shown in Fig. 7, where the oscillator's signal is shown as being measured with a spectrum analyzer using the "max-hold" function while changing the phase in the QM. The peaks in Fig. 7, which represent the available spectrum (AS), are spaced apart by the FSR. The max-hold spectrum was recorded for two different settings of the phase shifter in the oscillator's loop. The difference in the phase for these two settings is π. The two ASs are marked as *available spectrum 1* and *available spectrum 2* in Fig. 7.

As is known from [1], the change in frequency for an FSR means an exactly 2π phase change in the OEO's loop. This is one of the reasons for the repetitive character of the AS along with the Barkhausen amplitude criterion and the phase interactions between the FQM and the OEO's loop. The AS is wider if

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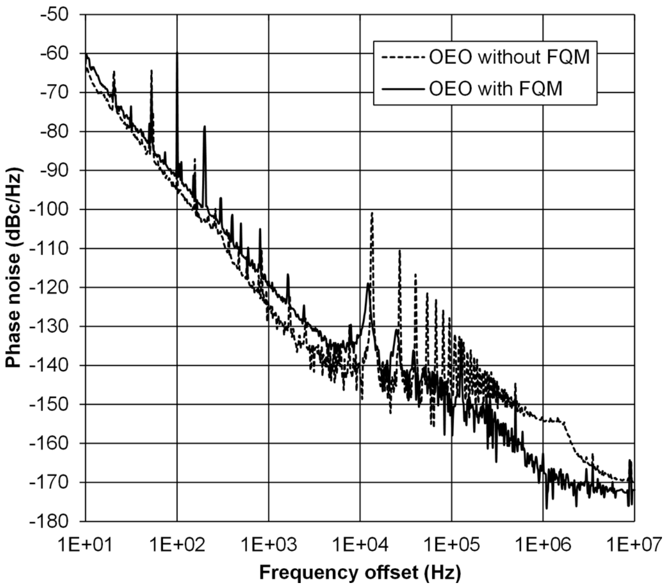

Fig. 8. Phase-noise comparison between the OEO with and without the FQM.

the amplifiers in the OEO's loop are deeper in terms of saturation.

To tune the OEO with the FQM for optimum loop conditions (a narrower FQM bandwidth), the phase shifter in the OEO loop has to be set to a value where there will be an odd number of peaks in the AS. In Fig. 7, this is shown as *available spectrum 2*. The phase in the QM then has to be set to a value where the OEO will oscillate at the middle peak in the AS.

B. Phase Noise

In Fig. 8 the phase noise of the OEO with the FQM is compared to the OEO without the FQM. The latter was also constructed and measured in our laboratory. Single-mode operation was achieved with the same bandpass filter as is shown in Fig. 2 for the FQM. To compensate for the insertion loss of the passive bandpass filter, additional amplifiers were added in the loop.

It is clear that the FQM increases the phase noise. The increase at the 10-Hz offset was approximately 2 dB, and at 1 kHz it was 4 dB. The lowest phase noise before the first side mode was −140 dBc/Hz at 8 kHz in an OEO without an FQM. When the FQM was added, the phase noise increased to a value of −135 dBc/Hz at 7 kHz. This means an increase in the phase noise by 5 dB. The decrease in the frequency is due to the increased delay time in the OEO's loop because of the FQM.

Despite the phase-noise increase due to the FQM, it increases the SMSR by 18 dB for the first side mode. For the second and third side modes, the increase in the SMSR equals 20 dB.

In Table I, the power levels at the input and output of the FQM are shown. The input and output power levels are approximately 10 dBm. This means that the FQM gain is 0 dB and that the reduction factor of the filter's bandwidth equals 8. In this case the OEO's open-loop bandwidth was 45 kHz instead of 360 kHz.

IV. Comparison and Discussion

In Table II, the performance parameters of the DIL OEO [8], the dual-loop OEO [6], and the OEO with an optical filter (Fabry–Perot etalon) [12] are compared to the OEO with the FQM. These three configurations of OEO were chosen because they have the closest SMSR to our experimental OEO of all the configurations mentioned in Section I. It can be seen that the DIL OEO and the OEO with an optical filter are better than the OEO with the FQM and the dual-loop OEO with respect to the SMSR.

The DIL OEO [8] has by far the best SMSR presented in the literature to the best of our knowledge. The OEO with an optical filter had an open-loop bandwidth of 15 kHz, which was three times narrower than our FQM. The dual-loop OEO seems to perform worse. As is clear from Table II, the authors in [6] report that they managed to suppress the side modes below the phase-noise level, which was at −110 dBc/Hz at the FSR offset. It should be noted that the SMSR in the dual-loop OEO and the OEO with the optical filter could be higher if the authors were able to achieve a lower phase noise. The authors of the dual-loop OEO presented in [5] achieved a phase noise of approximately −140 dBc/Hz for offset frequencies higher than 10 kHz (without considering any unwanted peaks). However, the SMSR of their OEO was still higher than that of the dual-loop OEO from Table II.

The DIL OEO and the OEO with the optical filter have a better SMSR than the OEO with the FQM. The main advantages of the OEO with the FQM are a smaller number of components than the DIL OEO and more easily obtainable components than the OEO with the optical filter. The DIL OEO requires two OEOs. The OEO with an optical filter uses a Fabry–Perot etalon, which is a very specialized component. This considered, the OEO with the FQM represents a more economical solution. Besides that, the OEO with the FQM in our experiment had the

TABLE I
FQM Signal Levels and Bandwidth

FQM input power	10.1 dBm
FQM output power	10.1 dBm
FQM gain	0 dB
Factor M	8
Bandwidth	45 kHz

TABLE II
Comparison of OEOS With Different Structures

Parameter	OEO with FQM	DIL OEO [8]	Dual-loop OEO [6]	OEO with optical filter [12]
Frequency	3 GHz	10 GHz	12 GHz	10 GHz
Open-loop bandwidth	45 kHz	8 MHz	85 MHz	15 kHz
Fiber length	15 km	6 km / 50 m	10 km / 5.5 km	2 km
Phase noise (@1kHz)	-119 dBc/Hz	-132 dBc/Hz	-90 dBc/Hz	-100 dBc/Hz
SMSR	120 dB	>140 dB	>110 dB	>130 dB
FSR	12.4 kHz	34.8 kHz	18.3 kHz	Not specified

longest fiber and thus the lowest FSR. A low FSR increases the SMSR.

Our experimental OEO had a lower operating frequency than the other configurations, as can be seen from Table II. To achieve similar results at higher frequencies the FQM's multiplication factor should increase because of the wider bandpass filter. This would affect the phase-noise performance, but should maintain the SMSR ratio. However, further investigations are necessary. A fair comparison of the phase-noise performance is not possible at this stage because of the different frequencies and the different fiber lengths.

V. Conclusion

The OEO with the FQM represents an effective low-cost solution to increase the SMSR. The phase noise is increased as an unwanted side effect, probably due to the residual phase noise of the FQM, as a result of the increased flicker noise and the noise figure of the FQM. Experiments at higher frequencies are planned in the future to additionally evaluate the properties of the OEO with the FQM for a comparison with other solutions.

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