ADJUSTABLE TIME DELAYS FOR OPTICAL CLOCK RECOVERY SYSTEMS

BY

AMIR ALI AHMADI

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
A. J. CLARK SCHOOL OF ENGINEERING
UNIVERSITY OF MARYLAND, COLLEGE PARK
DECEMBER, 2004
This research has been conducted in the Ultra-fast Photonics Laboratory of the Electrical and Computer Engineering department of the University of Maryland through the Research Internships in Telecommunications Engineering (RITE) program since June 1, 2004 until present.
ACKNOWLEDGEMENTS

Special thanks to the following:

- Dr. Thomas E. Murphy, for his constant mentorship and oversight of the research project, specially his efforts in creating a collegial environment where ideas could prosper. Furthermore, his ability at generating an organized daily plan and having an “Open Door” policy really enhanced the working atmosphere.

- Reza Salem, for his patience in hearing every question and taking the time to answer them. His dedication to research, work ethics and overall superior intelligence are an inspiration to me.

- Paveen Apiratikul, Elric Von Eden, and Audrey Strunc, for their constant help in the laboratory and for providing a friendly working environment.

- Finally, the MERIT Program and all the involved individuals for giving us this great opportunity to prepare for our future endeavors.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>TWO-PHOTON ABSORPTION AND OPTICAL CLOCK RECOVERY</td>
<td>2</td>
</tr>
<tr>
<td>OPTICAL TIME DITHERING SYSTEM DESIGN</td>
<td>5</td>
</tr>
<tr>
<td>COMPENSATING FOR THE TIME DELAY CAUSED BY THE PHASE- MODULATOR</td>
<td>6</td>
</tr>
<tr>
<td>FINDING THE HALF-WAVE VOLTAGE</td>
<td>8</td>
</tr>
<tr>
<td>EXPERIMENTAL SETUP AND RESULTS</td>
<td>10</td>
</tr>
<tr>
<td>AN OPTICAL CLOCK RECOVERY SYSTEM</td>
<td>12</td>
</tr>
<tr>
<td>USING TIME DITHERING AND TPA</td>
<td>15</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>18</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>19</td>
</tr>
<tr>
<td>CIRCUIT DETAILS AND PSPICE SIMULATIONS</td>
<td></td>
</tr>
<tr>
<td>REFERENCES</td>
<td>27</td>
</tr>
</tbody>
</table>
ABSTRACT

We introduce an all optical clock recovery system based on two-photon absorption (TPA) in a silicon avalanche photodiode. The system is polarization-insensitive, compact, broadband, and capable of supporting future high-speed optical networks. One key element in this new system is an adjustable time delay that allows the clock timing to be modulated. This was accomplished by using a phase modulator and polarization maintaining fiber to periodically dither the clock signal. Finally, a phase detector circuit followed by a phase-locked loop (PLL) can synchronize the clock and data signals.

INTRODUCTION

Clock recovery, the process of synchronizing a locally generated clock signal to a random stream of incoming data, is one of the first and most essential stages in any optical receiver, transceiver, 3R regenerator, or demultiplexer. In present-day optical networks, the task of clock recovery is handled in the electrical domain rather than the optical domain; at the cost of having optical-electrical conversion. However, in future high-speed optical networks, the data rate could exceed the speed of available electronic circuits, making it difficult to apply conventional electrical techniques. At such high bit-rates, clock recovery is best achieved using an optical scheme.

As a solution to this problem, nonlinear optical processes, such as two-photon absorption (TPA), can be employed to measure the relative timing difference between clock and data signals. Then, a phase-locked loop (PLL) can drive this difference to zero and synchronize the signals.

In any optical system, one main challenge is to design a polarization-insensitive scheme. The incoming data signal to an optical network can have any arbitrary state of polarization. So, it is important for the clock recovery system to effectively operate irrespective of the polarization of the data. However, it has been shown that the change in the polarization of data can shift the timing of the recovered clock generated by the system based on TPA [1]. In order to overcome this limitation, we built an adjustable time delay system (the dithering system), which allows the timing of the clock signal to be periodically modulated.
In this report, I briefly explain the operation of an optical clock recovery system based on two-photon absorption, and the reason for its polarization dependence. Then, I describe the design and implementation of an optical time dithering system in detail, and finally explain how time dithering can be combined with the previous structure to produce a polarization-insensitive clock recovery system.

**TWO-PHOTON ABSORPTION AND OPTICAL CLOCK RECOVERY**

A linear detector creates a single electron-hole pair by absorbing one photon. Therefore, the resulting photocurrent is a linear function of the incident optical power. However, a nonlinear detector, such as silicon avalanche photodiode (Si APD), under certain conditions, absorbs two photons to generate one electron-hole pair. In this case, the resulting photocurrent is proportional to the square of the optical power. This phenomenon is known as two-photon absorption (TPA) [2]. The nonlinearity of TPA, along with its advantageous properties, like ultra fast response time and broad spectral bandwidth, makes it an interesting technique for many optical applications, such as optical auto- and cross-correlations, optical sampling systems, and optical demultiplexers [1].

The idea of using TPA for optical clock recovery was recently introduced and implemented by Thomas E. Murphy and Reza Salem from University of Maryland, College Park, for the first time in the history of optical communications. The idea is to employ TPA for phase detection, which is indeed one of the most critical components of a clock recovery system. Phase detection is the task of determining the relative timing difference between the data and clock signals. As illustrated in figure 1(a), (b), if we combine and focus the clock and data signals onto the surface of a TPA photodiode, the time-averaged TPA current is larger when they are aligned ($\tau = 0$), than when they are misaligned($\tau \neq 0$). In other words, the amount of this photocurrent is determined by the relative timing difference of the two signals incident to the surface of the nonlinear detector. A linear detector, on the other hand, would produce the same amount of time-averaged photocurrent regardless of the timing delay between the two signals.
Fig. 1  (a) Optical clock and data signals with a relative phase difference of $\tau$ are combined in a nonlinear photodetector. (b) The time-averaged TPA current produced by SI APD is a periodic function of the relative delay. This photocurrent is largest when the clock and data are aligned ($\tau = 0$). (c) After the background offset is subtracted from this photocurrent, the resulting signal can be incorporated in a phase-locked loop, which locks the frequency of clock and data together.

As shown in figure 1 (b), the photocurrent has a non-zero background level because the data or clock can each separately produce TPA current even when they are non-overlapped. This background offset avoids the possibility of using the signal in a phase-locked loop (PLL), because phase-locked loops are designed to minimize a signal and require zero-crossings to lock to. Consequently, the offset should be subtracted before entering the PLL (Fig 1 (c)). Figure 2 shows how a PLL can be used to synchronize the clock and data signals.

Fig. 2  After the background photocurrent is subtracted, the resulting signal is incorporated in a PLL to synchronize the clock and data signals.
The presented optical clock recovery system is compact, high speed, broad band, and operates with a low optical power. The system has been successfully tested for data rates up to 12.5 Gb/s [1] and 80 Gb/s [9], with wavelengths ranging from 1530 nm to 1570 nm, and is expected to work for much higher data-rates and wider wavelength ranges. Such advantages make the system desirable for future high speed optical networks. However, this system is not yet completely polarization-insensitive. Recent work has shown that if we choose a fixed circular polarization for the locally generated optical clock signal, the cross-correlation contribution of the TPA photocurrent vs. delay ($\tau$) will remain constant regardless of the state of polarization of the data [3] (Fig 1_ (b)). But the amount of background level of this signal varies depending on the polarization of the data, while a fixed offset is always being subtracted from the signal (Fig1_ (c)). The change in the background photocurrent can directly cause a shift in the timing of the recovered clock. This shift can be as large as 8 ps for the 12.5 Gb/s system [1], and 1.1 ps for the 80 Gb/s one [9]. Furthermore, when the polarization of the incoming data fluctuates, a corresponding unwanted timing jitter is generated in the recovered clock.

In order to overcome this issue, we needed to somehow remove the background photocurrent without simply subtracting it. One quick solution that comes to mind is differential detection. As shown in figure 3, the data (or clock) is divided into two equal signals. We apply a time delay to one of the two and combine both signals with the clock to the surface of the nonlinear detector. A PLL may then be used to drive the resulting error signal to zero.

![Fig.3](image)

**Fig.3** [4] Differential detection as a solution to removing the background photocurrent

As you can see, this technique requires two photodiodes instead of one. Since TPA is a very weak effect, it is hard to accurately synchronize the two detectors.
Finally, we propose an optical time dithering system to solve the problem. The next section is dedicated to the design and implementation of this system.

**OPTICAL TIME DITHERING SYSTEM**

A time dithering system periodically modulates the timing of an optical signal (the clock signal for our case) between two states (figure 4).

![Figure 4](image.png)

Fig.4 The objective of the optical dithering system is to periodically dither the clock signal between two states.

One simple mechanical way to achieve this is to use a vibrating optical corner cube\(^1\). The light coming out of the cube will have a delay with respect to the light going in, and the amount of this delay can be modulated by moving the cube back and forth with respect to the source. But, such a system will be very low speed, inaccurate, and noisy. Also, since light has to travel through free space, the design is undesirable for integrated fiber-optic technologies.

Time dithering of an optical signal has been done electronically for applications such as clock recovery and data recognition [6]. However, with future data-rates exceeding the speed of electronic circuits, we are forced to do this task in the optical domain. We have successfully built an optical time dithering system, and to the best of our knowledge, there are no reports in the literature describing such a system.

---

\(^1\) Corner Cube Retro-Reflectors have three mutually perpendicular surfaces. A beam entering the effective aperture is reflected by the three roof surfaces and emerges from the entrance/exit surface parallel to itself [5].
DESIGN

Figure 5 shows the overall design of the system. The two main components of the dithering scheme are: the electro-optic phase modulator (PM), and the polarization maintaining fiber (PMF).

The electro-optic phase modulator changes the phase of an optical signal by applying an electric field along one of the crystal’s principal axes. Light polarized along this axis experiences an index of refraction change, hence an optical path length change, which is proportional to the applied electric field. The phase of the optical signal exiting from the crystal therefore depends on the applied electric field [7]. Applying an external periodic modulation (Shown as electrical modulation in Fig. 5) produces a periodic phase shift in the optical clock signal:

$$\Phi(t) = m \sin(\Omega t)$$  \hspace{1cm} (1)

Where $\Phi(t)$ is the change in phase, $m$ is the modulation index, and $\Omega$ is the modulation frequency. A commonly used voltage for electro-optic modulators is the half-wave voltage ($V_\pi$). It is defined as the voltage required to produce an electro-optic phase shift of 180°.

Since the phase shift occurs along one of the principal axes and not the other, the optical signal undergoes a change in the polarization state by traveling through the PM. By applying $V_\pi$ to the phase modulator, the polarization of the incoming light changes to its orthogonal state. For instance, by using the first polarization-controller we can set the polarization of the light going into the PM to linear +45°, which can be synthesized from two orthogonal linear waves of equal amplitude.
When the half-wave voltage is applied to the phase modulator, the polarization of the output signal dithers between two orthogonal states (in this case +45° and -45°, linear).

As illustrated in figure 6, the output optical signal undergoes a phase shift of 180° when the external voltage is $V\pi$, and a phase shift of 0°, when it is zero. As a result, the output signal dithers between two orthogonal states of linear +45° and linear -45°, at the frequency of modulation. At this stage, the task of the phase modulator is completed.

Polarization maintaining fiber (PMF) is a birefringent material with orthogonal slow and fast axes. Light travels at different speeds through the axes creating a timing delay between the two components. The amount of delay can be calculated from:

$$
\tau = \frac{\Delta n L}{c}
$$

Where $\Delta n$ is the difference between indices of refraction of the slow and fast axes (the birefringence of the material), $L$ is the length of the PMF, and $c$ is the speed of light in vacuum.

We aligned the slow and fast axes of the PMF with the +45 and -45 linearly polarized light coming from the phase modulator. As shown in figure 7, depending on the input polarization of the light, only one of the axes of the PMF is taken at a time, leading to a time delay of $\tau$ on the output signal.

1. As long as polarization controllers 1, and 2 (Fig. 5) are set to the right position, other orthogonal states of polarizations will equally do the job for this dithering system.

2. A birefringent crystal is a transparent crystalline substance that is anisotropic relative to the velocity of light [8].
Fig.7  The phase modulator periodically changes the input polarization between the blue and red states and therefore creates a dithering on the output of the PMF.

There were a couple of obstacles that had to be overcome before implementing the optical dithering system. The wave-guide inside the phase modulator also acts as a birefringent material, causing the signals to walk off from one another. So, we needed to somehow precisely measure this amount of unwanted delay and then remove it by some means. The other issue was the determination of the half-wave voltage \((V\pi)\) for the phase modulator.

In the next two sub-sections, I will describe our approach and solution to these problems in much detail.

**COMPENSATING FOR THE TIME DELAY CAUSED BY THE PHASE- MODULATOR**

When light travels through a birefringent material, a phase shift is created between the slow and fast components. The amount of this phase shift is given by:

\[
\Delta \varphi = \frac{2\pi \Delta n L}{\lambda}
\]

Where \(\lambda\) is the wavelength of light and other parameters are the same as equation 2. If we use a linear polarizer on the output of the birefringent material\(^1\), the spectral power of the outcome will be a periodic function of the wavelength, with peak values corresponding to phase shifts that are integer multiples of \(2\pi\) (Equation 3). Therefore, for two consecutive peaks we can write:

\(^1\) In our case, the birefringent material is the wave-guide of the phase-modulator along with its 48 cm input PMF.
\[ \Delta nL = \frac{\lambda_1 - \lambda_2}{\Delta \lambda} \]  

We used the output of the erbium-doped fiber amplifier (EDFA) as a broadband source to vary the wavelength and measured \( \Delta \lambda \) to be 0.66 nm. Using equations 4 and 2, a time delay of 12.1 ps is obtained.

In order to compensate for this delay, we added 7.42 meters of PMF, with a birefringence of \( 4.91 \times 10^{-4} \), before the phase modulator\(^1\). The slow and fast axes of the PMF and the PM were mismatched by using a polarization controller in between the two (PC 2 in Fig. 8). Therefore, the delay coming from the PM was canceled out by the opposite and equal amount of delay coming from the new length of PMF. Figure 8 illustrates the setup that we used for this experiment.

**Fig. 8** The experimental setup used for compensation of the PM time delay.

The results of this experiment are summarized in figure 9. Fig. 9\_a was obtained when PC2 was directly matching the slow and fast axis of the 7.42 meter PMF and the PM, leading to very small values of \( \Delta \lambda \) (equation 4) and therefore more overall time delay (equation 2). Fig. 9\_b was obtained from 9\_a by changing the polarization of light by 90° linear using PC2 and keeping everything else fixed. Notice that all the fringes are gone and the delay is being canceled. At this stage, PC2 should remain constant for the rest of the dithering experiment. Fig. 9\_c shows the spectrum of the EDFA on the optical spectrum analyzer (OSA). Fig. 9\_d, which has the same shape as

\(^1\) We calculated the birefringence by applying the same method (equation 3).
9_c, is the output of the overall setup of fig. 8, confirming the fact that the unwanted delay has been canceled.

![Graph](image)

**Fig. 9**

(a) Axes of the PMF and PM are matched.

(b) Axes of the PMF and PM are mismatched.

(c) Spectrum of the EDFA.

(d) The output of fig. 8.

**FINDING THE HALF-WAVE VOLTAGE**

Recall the periodic phase modulation formula 1: \( \Phi(t) = m \sin(\Omega t) \). The phase-modulated signal can be represented as a set of Fourier components in which power exists only at the discrete optical frequencies \( \omega \pm k \Omega \) [7].
Where $k$ is an integer, $m$ is the phase-modulation index (modulation depth), and $J_k(m)$ is the ordinary Bessel function of order $k$. This gives us a clue to indirectly solve for $V\pi$ by looking at the spectrum of the modulated light. A simple schematic of our experimental setup is illustrated in figure 10. We used the polarization controller to maximize the amount of modulation performed by the PM. A phase shift of $\pi$ is obtained when we achieve the most amount of modulation.

\[
E_{pm} = E_0 e^{j[\omega t + m\sin\Omega t]}
\]
\[
= E_0 \left\{ \sum_{k=0}^{\infty} J_k(m)e^{jk\Omega t} + \sum_{k=0}^{\infty} (-1)^k J_k(m)e^{-jk\Omega t} \right\} e^{j\omega t}
\]  

(Fig. 10) The experimental setup for measuring $V\pi$.

A high frequency function generator was used for external modulation at 7GHz\(^1\). The power coming from this function generator was varied throughout the experiment, to get closer to $V\pi$ by trial and error. Finally, an OSA was used to observe the power spectrum. The results shown in figure 11 correspond to a modulation power of 15.87 dBm, as measured by the radio frequency spectrum analyzer (RFSA). While all the power is concentrated at the center wavelength of the continuous wave (CW) unmodulated light (Fig. 11_ (a)), after phase modulation five noticeable sidebands are observed (Fig. 11_ (b)). The peak values of these components are listed in table 1.

---

\(^1\) Notice that we modulated at a high frequency in order to observe the results on the OSA for a very short range of wavelengths. The half-wave voltage is expected to be independent of the modulating frequency at the ranges required for dithering.
These values were fed to a MATLAB program to calculate the best fit to the Bessel distribution given in equation 5. The value of $m$, the modulation index, was found to be $1.61 \approx \pi / 2$. This results in a desired phase shift of $\pi$, as given by equation 1. The power shown by the RFSA (15.87 dBm) is conventionally known to be the average power that it delivers to a 50 Ohm resistor. This average power is equal to the square of the voltage amplitude divided by twice the resistance. Solving this equation for the voltage, we end up with 3.93 Volts, as the peak to peak value for $V\pi$.

### Table 1. Peak values of figure 11.

<table>
<thead>
<tr>
<th>Side Band</th>
<th>Peak value (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.985</td>
</tr>
<tr>
<td>2</td>
<td>4.745</td>
</tr>
<tr>
<td>3</td>
<td>-6.324</td>
</tr>
<tr>
<td>4</td>
<td>-19.989</td>
</tr>
<tr>
<td>5</td>
<td>-34.746</td>
</tr>
<tr>
<td>Center Peak</td>
<td>10.44</td>
</tr>
<tr>
<td>No Modulation</td>
<td>16.781</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL SETUP AND RESULTS**

Figure 12 illustrates our finalized experimental setup for the optical time dithering system. An intensity modulator is used to produce a 10 GHz optical clock signal from CW light. In order to get a clear output we need to amplify this signal using EDFA. After
the EDFA, a variable attenuation is needed to make sure not too much power is given to the system. As mentioned earlier, the 7.42 meter PMF is used to compensate the birefringence effect of the phase modulator. The actual PMF that we used for creating the dithering delay was about 18 meters, with a birefringence of $4.91 \times 10^{-4}$. From equation 2, we can calculate the timing delay, $\tau$, to be 29.5 ps. One other flexibility of the system is that the amount of this delay does not necessarily need to be so accurate, as long it is compatible with the data rate. Also notice in figure 12 that external square-wave modulation is applied to the phase modulator with a peak to peak voltage of $V_\pi = 3.93$ V, at 200 KHz. This frequency may also be varied depending on the desired application. The phase modulator that we employed in the system, is capable of handling speeds up to 10 GHz. For our particular task of clock recovery this frequency does not need to be very high. In the next section, I will explain some limitations on this frequency.

![Diagram](12)

**Fig.12** The final experimental setup for the optical time dithering system.
Figure 13 shows the actual result of the dithering system with the specified values, on the sampling oscilloscope. As you can see, time dithering is observed quite neatly. Some random dots are present on the picture, corresponding to some intermediate polarization states coming out of the PMF. At higher dithering frequencies (1MHz and above) we will have more unknown polarization states which can be troublesome for the clock recovery system. In order to avoid this problem, a better square-wave generator, with fewer amounts of over shoot and a shorter rise time, should be employed. However, at 200 KHz this effect is negligible.

![Diagram showing time dithering with τ = 31.7 ps and T = 100 ps](image)

**Fig.13** The output of the dithering system on the sampling oscilloscope.

Our optical time dithering system has several advantages over other similar schemes, which make it a useful technique to apply in an optical clock recovery system or other optical applications.

- No moving parts as opposed to traditional mechanical methods.
- Ability to provide very high dithering frequencies up to 10 GHz.
- Modulates the clock in the optical domain rather than the electrical domain.
- Satisfies the requirements of high data rate communications.

In the following section, I will explain how we can use the dithering system in an optical clock recovery system based on TPA.
AN OPTICAL CLOCK RECOVERY SYSTEM USING TIME DITHERING AND TPA

As discussed earlier in the report, Time dithering and TPA can be combined to provide a polarization-insensitive optical clock recovery system. The idea is to somehow use the two-photon absorption current in a PLL to synchronize the clock and data signals. If we combine the time-dithered clock with the data signal, and focus it to the surface of the TPA detector, the output photocurrent can be used with a phase-detection circuit in a phase-locked loop. As shown in figure 14, when data is not aligned with the clock signal, it has two different delays with respect to the dithered clock. As a result, the TPA current will periodically vary between two states, at the dithering frequency. This is illustrated as a square wave in fig. 14. Obviously, if data were aligned with the clock, this square wave would ideally become a straight line ($\tau_1 = \tau_2$).

In order to use this signal in a PLL we need a phase-detection circuit. The circuit that we built consists of an amplifier, mixer, and a low-pass filter (LPF) (figure 15). Since the amplitude of the TPA signal is very small (in the order of a few mili volts), we need to amplify it by a factor of about 10 to 20. The limited bandwidth of the available amplifiers put a restriction on our dithering frequency, since it is harder to amplify at higher frequencies. For a better performance, we decided to work with a double stage non-inverting amplifier. The mixer that we used was an AD734. It multiplies the...
amplified TPA output by a branch of the reference electrical modulation signal, which was used for dithering. Since the two signals going into the multiplier have the same frequency (200k), the output will have a double frequency component and a DC level component, which represents the average value of the signal. We had a second-order active Butterworth LPF in the circuit, right after the mixer. The 3dB bandwidth of this filter was measured by the network analyzer to be 16.9 KHz. So, this LPF will almost completely block out the high frequency components and keep the DC offset. For the situation shown in figure 14, this final offset is negative. If $\tau_1$ was less than $\tau_2$, the offset would be positive, and if they were equal the LPF would produce an output of zero. The special design of the phase-detection circuit therefore allows the output of the LPF to be incorporated in a phase-locked loop to synchronize the clock and data signals.
Fig.15  The phase-detection circuit.
Figure 16 shows an overall block-diagram of the clock recovery system, which utilizes the dithering system.

**Fig.16** The overall block diagram of an optical clock recovery system, which uses an optical time dithering system

## CONCLUSIONS

We present an all optical clock recovery system using two-photon absorption in a silicon avalanche photodiode. Unlike many other nonlinear approaches for optical clock recovery, this system is compact, broad band and scalable to very high data-rates required for future high-speed optical networks. The novel idea of an optical time dithering scheme, makes the system completely polarization-insensitive. This system periodically dithers the timing of an optical clock signal between two states, 30.7 ps apart in time, at 200 KHz. A prototype of the dithering system was successfully built using an electro-optic phase modulator and polarization maintaining fiber. In order to utilize the dithering system in the structure of the actual clock recovery system, a phase-detection circuit consisting of an amplifier, mixer, and a second order active low-pass filter was implemented. Finally, a phase-locked loop will be used to synchronize the clock and data signals.
APPENDIX A

CIRCUIT DETAILS AND PSPICE SIMULATIONS

DOUBLE STAGE AMPLIFIER

Double stage amplifier with two high-pass filters.
- Op-Amps in the actual circuit: **OP27**.
- Op-Amps used for simulations: **LF411**.
- 3dB bandwidth of the input HPF: **1.8 KHz** (By the network analyzer).
- 3dB bandwidth of the output HPF: **15.9 KHz** (By calculation).

A sinusoidal input-output pair for the double stage amplifier circuit\(^1\).

\(^1\) The double stage amplifier circuit is the overall circuit shown in the picture. (It includes the two HPFs).
A square-wave input-output pair for the double stage amplifier circuit.

Frequency response of the double stage amplifier circuit.
LOW-PASS FILTER

Second order active Butterworth LPF.

- Op-Amp in the actual circuit: LF355N.
- Op-Amp used for simulations: LF411.
- 3dB bandwidth: 16.9 KHz (By the network analyzer).
- Stop-band roll off rate: 35 dB/dec. (By the network analyzer).
Frequency response of the LPF with a LF411 Op-Amp.
THE OVERALL PHASE-DETECTION CIRCUIT

The phase-detection circuit.
The output of the multiplier (red) and the LPF (green).

The output of the multiplier and the LPF, when the TPA input is inverted (v1 and v2 of Vtpa are swapped).
DETECTOR CIRCUIT

The detector circuit (to convert the photocurrent to voltage).

Frequency response of the detector circuit.
REFERENCES


5. Optical Components, Redoptronics Company.


7. Practical Uses and Applications of Electro-Optic Modulators,
   http://www.newfocus.com/Online_Catalog/literature/apnote2.pdf

8. The Photonics Dictionary,
   http://www.photonics.com/dictionary/