Experimental and theoretical investigation of a sub-threshold OEO for RF sensing of constant and time-varying signals

Brenden Glover$^1$, Michael O. Osisanya$^1$, Gautam Vemuri$^1$, and Joseph S. Suelzer$^1$

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Abstract

We experimentally characterize and numerically model the amplification characteristics of a sub-threshold opto-electronic oscillator subject to external continuous wave radio frequency injection, as well as the transient temporal characteristics when subject to a pulsed radio frequency injection. The opto-electronic oscillator demonstrates enhanced sensitivity and amplification as threshold is approached. A radio frequency gain of 27.5 dB is demonstrated at an optical power of 0.989 times the threshold optical power. Furthermore, the transient behavior shows signatures of both the intrinsic time-delay of the opto-electronic oscillator and the finite bandwidth of the electronic radio frequency filter. Approximating higher-order group delay contributions of the experimental band-pass filter as an external time-delay allows the system to be modeled with a well-known opto-electronic oscillator rate equation model. The nonlinear, time-delayed differential equation model provides numerical agreement with experimental results. The model is approximately solved in respective analytical and transcendental regimes, giving reliable predictions compared to the experiment. It is demonstrated that small time-delay variation yields precise and predictable control over the frequency selectivity of the opto-electronic oscillator sensor.
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Index Terms—Opto-electronic oscillator, enhanced sensitivity, time-delayed rate equations, selective RF amplification

I. INTRODUCTION

THE use of an optoelectronic oscillator (OEO) for low phase noise RF signal generation was first demonstrated in 1996 [1]. In a typical OEO system, an optical signal is electro-optically modulated and subsequently detected by a fast photodiode. The photodetector output voltage is amplified, sent through an electronic filter, and directed back to the electro-optical modulator, forming a cavity. When the system gain exceeds the cumulative loss, an oscillating signal emerges from the system’s noise [2]. The noise is derived from the active optical and electronic components in the system cavity including the optical source, photo-detection, and electronic or optical amplification. Depending on the system parameters, the OEO can exhibit multi- or single-mode oscillation. The frequency spacing of these modes is governed by the effective propagation length of the OEO system (including optical fibers, electrical cables, filters, etc.). These cavity modes can be depicted and measured by an electrical spectrum analyzer (ESA).

For nearly three decades, experimental and numerical investigations have led to improved phase noise [3-5], frequency tuning [6,7], and significant size reduction [8-10]. Furthermore, the OEO has served as a testbed for nonlinear dynamical studies where a rich variety of operating regimes have been demonstrated. These dynamic regimes emerge due to the intrinsic nonlinearity, time-delayed feedback, and response times of the electronic/photonic components [12-14]. A phenomenological model using time-delayed differential equations has shown excellent agreement with experiments capturing steady-state (CW) operation, multimode behavior, period-doubling, and chaos [12,14]. In addition to serving as a testbed for nonlinear dynamical studies, the OEO has been investigated and used as a system for sensing, measurement, and detection where environmental perturbations affect the operating conditions of the free-running OEO [15]. Several studies have focused on the sensitivity to, and detection of, external RF signals within an OEO architecture. These studies have leveraged multimode operation [16] to selectively amplify RF signals, investigate transient behavior under RF injection-locking [17], and employ phase-locked loops to enhance sensitivity of weak RF signals [18]. These studies rely on steady-state or multi-mode operation where the OEO is clearly above threshold with respect to the gain requirements.

In contrast, this work examines the sensitivity of a single-mode OEO operating just below (sub-) threshold, i.e. the trivial bifurcation, where the OEO begins to self-oscillate when the appropriate gain is reached. We investigate through experiments, analytic calculations, and numerical modeling whether a sub-threshold OEO can selectively amplify an injected RF signal, how the amplification depends on the

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OEO’s proximity to its oscillation threshold and frequency detuning relative to resonance, and whether the spectral selectively and frequency response of the sub-threshold OEO can be tuned via the external time-delay thereby obviating the need for a tunable RF filter. In addition, we investigate the transient response of the sub-threshold OEO system to injected, pulsed RF signals. We numerically model and experimentally characterize the gain-bandwidth as a function of the injection signal strength and frequency for various gain parameters (defined below). This fully characterizes the potential for selective RF amplification of the OEO near threshold.

With respect to the transient response of the OEO subject to pulsed RF signals, we distinguish and highlight the influence of the fixed time-delay (derived from the cavity length) and the contributions from the higher order filter group delays. The agreement between the numerical model, analytic predictions, and experiment for both steady-state and transient characteristics is discussed. Finally, we show the advantage of numerical simulations when operating in the pulsed regime. The experimental limitation of the pulsed signal generation has inherent rise/fall times of approximately 10 ns, where the step-size of the numerical algorithm employed for integration is on the order of 1 ps. This enables near instantaneous resolution of

The diagnostic branch enables temporal, spectral, and power measurements. A critical feature of this experiment is fine control over the internal gain of OEO, which is proportional to the optical power incident at the photodetector. The optical power is adjusted using a precision source measurement unit to electrically bias the EVOA. To determine the optical gain at threshold ($P_{th}$) of the OEO, a portion of the electronic signal from the PD was directed to an electrical spectrum analyzer (ESA) which provided more dynamic range and smaller noise floor compared to a conventional (8-bit) oscilloscope. The hybrid coupler, ESA, and oscilloscope relative injection/output losses are measured in reference to the output of the hybrid coupler, whose values are reported in Table 1.

III. MODEL OEO

To better understand and predict the operating dependencies of system parameters, we utilize and model the OEO with a time-delayed rate equation [12]

$$\frac{\partial^2 x}{\partial \Delta \omega^2} + \frac{1}{\Delta \omega} \frac{\partial x}{\partial t} + \frac{d x}{d t} = \frac{P}{P_{th} \frac{d}{d t}} \cos^2[x(t - T) + \phi],$$

where $x$ is the normalized voltage, $\phi$ is the normalized MZM bias-voltage, $\Delta \omega$ is the central angular frequency, $\Delta \omega$ is the angular bandwidth, $T$ is the time-delay, $P$ is the optical power, and $P_{th}$ is the optical power at threshold (condition for self-oscillation). Explicitly $P_{th} = 2V_n \pi L G_{th}$, where $V_n$ is the characteristic MZM half-wave voltage, $L$ is the photo-voltaic coupling of the photodetector, and $G_{th}$ incorporates all gain and loss from optical, electronic, and photonic components at threshold. The variables $x$ and $\phi$ are normalized to $\pi(2V_n)$ [12]. The OEO model bandwidth was set to the experimental bandwidth of 5 MHz measured with an electronic network analyzer.

One may construct an equivalent bandpass filter by combining an inductor of inductance $L$, a capacitor of capacitance $C$, and a resistor of resistance $R$ in an LCR series circuit. Applying Kirchhoff’s laws to an LCR circuit, the left-hand side of (1) describes the output voltage, $x(t)$, where the

![Diagram](image_url)
Additionally, the input voltage to the filter is described by the photocurrent which is proportional to the OEO internal optical power.

We next extend (1) to include an injected signal by adding an additional driving term $V_i \cos(\omega t)$ to the modulator input:

$$\frac{\Omega_0^2 V}{\Delta \Omega} + \frac{1}{\Delta \Omega} \frac{d^2 V}{dt^2} + \frac{dV}{dt} + \frac{k_{\text{out}}}{P_{\text{th}}} \frac{d}{dt} \cos^2 \left( \frac{V_i}{k_{\text{out}}} + \kappa_{\text{in}} V_i \cos(\omega t) + \phi \right)$$ (2)

Where $V_i$ and $\omega$ are the injected voltage amplitude (normalized $\pi/(2V_x)$) and angular frequency of the injected signal, $V$ is the normalized output voltage of the injected OEO ($V = x/k_{\text{out}}$), $V_i = V(t - T)$, $\kappa_{\text{in}}$ is the injection coupling from the signal generator to the MZM bias tee, and $\kappa_{\text{out}}$ is the output amplitude coupling. Depending on experiment $k_{\text{out}}$ may be equal to $k_{\text{OC}}$ or $k_{\text{ESA}}$ given in Table 1. To match the model to the experiment, the output coupling must be normalized to the loss from the filter to the MZM bias tee.

### IV. EXPERIMENT AND MODEL CHARACTERIZATION

To enable quantitative comparisons between the numerical model and experiments, we first characterize the relevant system parameters. We set the modulator bias to quadrature and account for all losses from the band-pass filter to the MZM. As depicted in Fig. 2(a), an analogous experimental filter’s higher-order components increase the group delay. The model filter, depicted in Fig. 2(b), compensates for this increase in group delay with a direct time-delay. The total time-delay ($T$) of the model is set to be $T = T_{\text{exp}} + \left( \frac{2(n-1)}{\Delta \Omega} \right)$. $T_{\text{exp}}$ is the delay measurement of all OEO components external to the filter and $n$ is the order number of the filter. The external delay is measured with a network analyzer. The bandwidth used within the model is equivalent to the 3-dB bandwidth from direct measurements of the various filters using a network analyzer.

Listed are the experimental parameters used to directly compare the model and experiment.

### Table I

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value *</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_0$</td>
<td>Band-pass Filter Central Frequency</td>
<td>1.00004 $2\pi$ GHz</td>
</tr>
<tr>
<td>$\Delta \Omega$</td>
<td>Band-pass Filter Bandwidth</td>
<td>5.2 MHzRadians</td>
</tr>
<tr>
<td>$V_i$</td>
<td>MZM Characteristic Voltage (oc angle / volts)</td>
<td>2.2135 V/Rad</td>
</tr>
<tr>
<td>$k_{\text{in}}$</td>
<td>Insertion Loss</td>
<td>5 dB</td>
</tr>
<tr>
<td>$k_{\text{ES}}$</td>
<td>Steady State Relative Output Loss</td>
<td>6.5 dB</td>
</tr>
<tr>
<td>$L_T$</td>
<td>Transient Relative Output Loss (dB)</td>
<td>7.085 dB</td>
</tr>
<tr>
<td>$\kappa_{\text{OC}}$</td>
<td>Model to Experimental Injection Voltage Ratio</td>
<td>0.797</td>
</tr>
<tr>
<td>$\kappa_{\text{ESA}}$</td>
<td>Oscilloscope to Output Voltage Ratio</td>
<td>0.334</td>
</tr>
<tr>
<td>$\kappa_{\text{ESA}}$</td>
<td>ESA to Model Output Voltage Ratio</td>
<td>0.3112</td>
</tr>
</tbody>
</table>

Additional parameters measured using a network analyzer are provided in Table 1. Cable and component losses were referenced to the RF signal driving the MZM. All intermediate component losses, including couplers, are accounted for within the model. The injection loss was measured from the input signal cable to the input of the MZM. The output loss included all losses from the band-pass filter to the ESA, which is normalized to the loss from the band-pass filter to the MZM. The characteristic voltage of the MZM ($V_{\text{th}}$) was obtained by initially finding the small signal loss from the input of the MZM bias-T to the output of the photodetector and subsequently solving for $V_{\text{th}}$ in the equation:

$$\frac{P_{\text{in}}}{P_{\text{out}}} = 4\pi \frac{I_{\text{in}}^2 R_{\text{out}} R_{\text{th}}}{V_{\text{th}}^2}$$ (3)

In conclusion, the model includes an additional driving term proportional to the OEO internal optical power. This term is added to the modulator input, allowing for the simulation of an injected signal. The equations and parameters are derived and listed to enable quantitative comparisons with experimental data. The model is validated by comparing measured and simulated results, demonstrating the accuracy and reliability of the approach.
V. MODEL PREDICTIONS

For a robust understanding of the injected OEO, we analyze the system from three perspectives: experimental, numerical model, and analytical solutions. An analytical solution gives the additional benefit of fast (compared to numerical integration), well-defined predictions. We derive an approximate analytical prediction for the output gain of the OEO by starting from the complex equivalent of (2)

\[
\left( \frac{\Omega_0^2 + D_i^2}{\Delta \Omega} + D_t \right) V = \frac{P_{\text{out}}}{P_{th}} D_t \cos^2 \left( \frac{V_i}{K_{\text{out}}} + \phi + K_{in} \psi_i e^{i(\omega_T t + \theta)} \right),
\]

where \(D_t\) is the time derivative operator. We assume solutions of the form, \(V = A e^{i\omega t} (V_c = A e^{i(\omega t - T)}).\) The first-order linear expansion around small amplitude solutions of (4) gives

\[
\frac{\omega^2 - \Omega_0^2}{\omega \Delta \Omega} + 1 = -\frac{P_{\text{out}}}{P_{th}} \sin(2\phi) \left( e^{-i\omega T} + \frac{K_{\text{out}} K_{in} V_i}{A} e^{i\theta} \right) \tag{5}
\]

where we assume the output frequency (\(\omega\)) is equal to the input frequency (\(\omega_T\)).

The modulus and phase of (5) is solved for amplitude gain.

We find

\[
\frac{A}{V_i} = \frac{K_{\text{out}} K_{in} A^4}{\alpha \cos[\theta] + \sqrt{\alpha^2 \cos^2[\theta] - 1} + \left( \frac{\omega^2 - \Omega_0^2}{\omega \Delta \Omega} \right)^2 + 1}, \tag{6}
\]

where \(\alpha = \frac{P_{\text{out}}}{P_{th}} \sin(2\phi)\) and

\[
\theta = \tan^{-1} \left( \frac{\alpha \omega T}{\omega \Delta \Omega} \right) + \omega T. \tag{7}
\]

Additionally, we find a transcendental relationship that extends to the nonlinear regime for the special case that \(\omega = \Omega_0\) or zero detuning from the central frequency. To achieve this, we utilize the Jacobi-Anger expansion on the \(\cos^2(\cdot)\) term of (4) to isolate the relevant central frequency contributions [12]. We find the transcendental equation

\[
A = K_{\text{out}} \alpha f_1 \left( \frac{2A}{K_{\text{out}}} - 2K_{in} V_i \right) \tag{8}
\]

where \(f_1(\chi)\) is the first Bessel function of the first kind. The global maximum of \(\max_{0 \leq x \leq 50} [f_1(x)] \approx 1.6\) limits the steady state amplitude to \(A < K_{\text{out}} \alpha 1.6\) or \(P_{RF} < (K_{\text{out}} \alpha 1.6)^2 / 2R\). Relevant results of (8) are discussed below (see Fig. 5).

VI. RESULTS

A. Amplification vs Injection Frequency

In general, the sensitivity or response of a device depends on the frequency content of the perturbation. To analyze the frequency response of the system under investigation, an external RF signal is injected into the OEO. The amplitude of the injected signal is fixed, and the injected frequency is scanned. This procedure is performed experimentally, numerically, and analytically. To analyze the response, we produce an output power (dBm) vs injection frequency (GHz) plot at a fixed RF injection strength and internal OEO gain, corresponding to -40 dBm and 0.891 \(P_{th}\), respectively. The results are shown in Fig. 3. In addition, we include the response for multiple time-delays. The experimental results are displayed by the solid lines. The dashed curves of Fig. 3 are the analytic predictions provided by (6) and the dotted curves are the simulated results from numerically integrating (2). The output loss, \(\kappa_{\text{out}}\), was set to be \(0.3112\) as given in Table 1. A value of \(\Delta T = 0\) corresponds to an external cavity delay of 296.5 ns with the OEO self-oscillating at the central frequency of the band-pass filter. Each non-zero \(\Delta T\) corresponds to incremental time-delay, 50 ps multiples, which is offset from 296.5 ns. An important effect of the time-delay on the gain bandwidth response function is to shift response along the frequency axis, which ultimately enables frequency tuning of the selective RF amplification.

As seen in Fig. 3, the analytic prediction and numerical data are identical over the entirety of the frequency sweep. This is expected because the chosen amplitude of the injected RF signal and the internal gain of the OEO enforce operation well within the linear regime. The experimental data agrees best with the model when the injection frequency is close to the central frequency. We note that the bandwidth over which the system exceeds unity RF gain was around 300 kHz. It should be noted this bandwidth can be adjusted by changing the optical power (i.e., internal gain) or time-delay (on orders of inverse filter bandwidth) and will depend on injection strength in the nonlinear regime.

As the injection frequency approaches a detuning near the HWHM of the band-pass filter response, the higher order group delay contributions of the experimental filter can no longer be treated as constant with respect to frequency variation. This causes quantitative discrepancies compared to the model that treats the higher order group delay contributions as a constant external cavity delay (see Fig. 2). A filter specific higher order
model can be developed by performing a complex curve fitting of the filter response function and augmenting the rate equation model to include the higher order terms. This would increase model accuracy for a broader range of injection frequencies but with a higher computational cost.

B. RF Output vs Input Power

In addition to the frequency response, we investigate the system RF output power and nonlinear saturation characteristics as a function of RF injection power. The OEO self-oscillating frequency and injection frequency are fixed at resonance, which corresponds to the central frequency of the band-pass filter. Fig. 4 displays the RF output power of the OEO as a function of the injected RF power for various gain values as threshold is approached. The blue, orange, yellow, purple, and green data points correspond to optical powers at 0.796, 0.891, 0.941, 0.974, and 0.989 times $P_{th}$, respectively. The error bars indicate the first standard deviation of RF output measurements.

For the four smaller gain values (blue, red, yellow, purple lines), the optical power and corresponding gain values were determined by the threshold fitting algorithm. Clearly as threshold is approached the external RF gain increases. For those values shown in Fig. 4, the response closest to threshold (0.989 $P_{th}$) exhibited the largest gain, approximately 27.5 dB, within the linear regime. However, as $P_{th}$ is approached small fluctuations of the internal gain/losses and time-delay cause relatively large shifts in the OEO output, and threshold was obscured. This effect added significant variation to the threshold fitting algorithm, and therefore we fit the experimental curve in the linear regime to the associated linear prediction given by (6) to calculate the optical power closest to $P_{th}$ (green in Fig. 4). Note that the RF output power (or equivalently the gain) can be increased by decreasing the input/output loss coefficients of the experimental design. For example, one can increase the effective gain by 7-dB by changing the output coupler shown in Fig. 1 from a 10-dB to a 3-dB coupler.

![Fig. 4. The dependence of the RF output power on RF input power for various percentages below the threshold optical power from the experiment. As threshold is approached, the RF output power saturates at a lower input power.](image)

To demonstrate the accuracy and predictive power of the OEO model, we examine the response at a gain value of 0.974 $P_{th}$ (see Fig. 4, purple data points). We compare and overlay the experimental results, plotted in blue, with theoretical results shown in Fig. 5. The numerically simulated results based on (2) are depicted by the orange dotted line, the yellow dashed lines are transcendental solutions of (8), and the linear approximation from (6) is given by the purple dashed and dotted lines. The output loss $k_{out}$ was set to be $k_{ESA} = 0.3112$. The transcendental and numerical model results agree with experimental results far into the nonlinear regime. The small discrepancies in the nonlinear regime could be caused by a combination of parameter drifts during the experimental characterization and higher order non-linearity. Similar theoretical and experimental agreements were found for all the gain values shown in Fig. 4.

C. Transient Characteristics

Within Subsections IV(A) and IV(B), we investigated the behavior of the OEO subject to injected CW signals, where our analysis was performed in the steady-state regime. However, most environmental signals are not static and exhibit some form of modulation. To determine the response functions of the system, we examine the extreme case where the OEO is subject to pulsed RF signals, i.e. square wave amplitude modulation. For all results in this section the internal gain was fixed at approximately 0.90 $P_{th}$. In this section alone, $P_{th}$ was estimated by visual inspection of the oscilloscope when the onset of oscillation was established.

Here we refer to the time it takes the OEO to reach its steady state value as the global transient response time. For the blue curve shown in Fig. 6(c), the global transient response time is approximately 5 μs. The global transient response time was investigated by observing the injected, pulsed RF signal (input) and the amplified RF signal (output) temporally on an oscilloscope. The RF pulses were created using a standard
pulsed amplitude modulation from a vector signal generator.

Fig. 6. Transient response to pulsed RF signals. The RF input power (blue) is fixed at (a) -20 dBm, (b) -10 dBm, (c) 0 dBm, and (d) 10 dBm. The system gain is fixed at 0.90 Pth. Discrete steps are captured in the output response. The global transient response time for the output signal is dependent on the input signal’s power.

The pulse width was increased to ensure that the amplified OEO signal reached a steady state before the input pulse was turned off. Similarly, the mean time between pulses was long enough for the power of the OEO to ring down before the next pulse was initiated. Using an oscilloscope, temporal data is measured for different system conditions (see Fig. 6) in which the response of four input signal powers (-20 dBm, -10 dBm, 0 dBm, and 10 dBm) was recorded. The frequency for all four input signals is approximately 1 GHz.

The global transient response time depends on the injected signal’s amplitude. In general, global transient response times decrease with increasing amplitude of the injected signal. This is expected due to the OEO system’s finite gain and inherent saturation. As shown in Fig. 6, the signal generated by the OEO approaches a steady state value through a series of steps whose duration will be referred to as the step time. As depicted in Fig. 6(d) the number of step times required to achieve the global transient response time is approximately three, which is significantly less than those shown in Figs. 6(a-c). The step time shown in Fig. 6 roughly matches the system time-delay (related to the system cavity length), and Fig. 6 shows the step time is independent of the injected signal power.

The effects of filter bandwidth and time-delay on the response times were numerically and experimentally investigated, and the key results are summarized in Fig. 7. The simulation was generated by numerically integrating (2), with the output loss coefficient set to κOC=0.334. Figs. 7(a) and 7(b) show the transient response for various filter bandwidths with a constant external time-delay. The duration of global transient response time is in good agreement between experiment and numerical model. We refer to the time it takes from the end of one step to transition to the flat portion of the next step as the transient step time (TST). For example, the purple curve in Fig. 7(b), ΔF = 5 MHz, the TST time is approximately 100 ns. The model and experiment show an inverse relationship between bandwidth and the TST. The amplitude discrepancies between experiment and numerical model are likely due to the inaccuracy of our estimate of Pth. To visualize the data shown in Figs. 7(a) and 7(b), the plotting order between the figures were rearranged. The experimental result indicated by an infinite bandwidth and shown in Fig. 7(a) corresponds to the absence of an RF filter. However, note that all components (e.g. photodetector, cables, and couplers) have a finite bandwidth, which are large compared to the oscillating frequency of approximately 1 GHz.

Fig. 7(c) and 7(d) capture the experimental and numerical response for various time-delays for a fixed filter bandwidth. Compared to the experimental results, an additional time-delay of 2/πΔF is added to the time-delay of the numerical results to account for the higher order experimental group delay contributions (see Fig. 2). The step time and global transient response time increase proportionally with the external cavity time-delay. Although there is good qualitative and quantitative agreement between Figs. 7(c) and 7(d), the experimental data
shown by the blue curve in Fig. 7(c), where $T = 142.5$ ns exhibits an additional amplitude modulation that is not identical to the numerical results. This amplitude modulation of period $\sim 2500$ ns appears to be an artifact of the oscilloscope most likely derived from the sampling rate.

The experimental and numerical results shown in Fig. 7 demonstrate that the model provided by (2) accurately captures the temporal response of the OEO for the parameter ranges described above. A future investigation would use complex curve fitting to create a phenomenological model of the experimental filter, which would include higher-order terms and augment the rate equation to improve the overall quantitative accuracy of the OEO model.

VII. CONCLUSION

In summary, we numerically, analytically, and experimentally investigate the sensitivity and response of an OEO subject to injected RF signals. The OEO was operated just below the first bifurcation, or sub-threshold, to demonstrate enhanced sensitivity as threshold is approached. Overall, there is an excellent agreement between the time-delayed rate equation model and experiments. Analytical and transcendental solutions (6,8) were obtained, and experimental agreement is demonstrated within the investigated operating regimes. It is shown that the sub-threshold OEO can selectively amplify an injected RF signal. For weak RF signals, the effective external gain depends on the OEO’s proximity to threshold and the frequency detuning relative to resonance. An RF gain of 27.5 dB was demonstrated at 0.987 $P_{th}$, which provides a measure of the system sensitivity to small signals. Furthermore, the spectral selectively and frequency response of the system can be finely tuned via the external time-delay, in some cases obviating the need for a tunable RF filter.

The transient response of the OEO was investigated by injecting a pulsed RF signal. The numerical model enabled near instantaneous resolution of the response times, which is limited experimentally by the response times of the signal generator and oscilloscope. We observed that the step time is independent of the amplitude of the injected RF signal, but that the global transient response time is inversely proportional. Finally, the transient analysis highlights the response constraints of the OEO in the presence of time-varying RF signals, where the filter bandwidth and external time-delay play an adverse role in the response time of the OEO.

REFERENCES


Brenden R. Glover was born in Pittsburgh, Pennsylvania, USA in 1997. He received the B.S. in physics from Indiana University of Pennsylvania, M.S. degree in physics from Indiana University-Purdue University Indianapolis, in 2021, and is pursuing his PhD in physics at Indiana University-Purdue University Indianapolis, IN. Mr. Glover began a Defense Associated Graduate Student Innovators fellowship in August 2024. His research interests include time-delayed, nonlinear dynamics of opto-electronic devices with a focus on coupled systems.
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