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A SUPER-REGENERATIVE OPTICAL RECEIVER BASED ON AN OPTOMECHANICAL OSCILLATOR

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ABSTRACT

A super-regenerative optical receiver detecting on-off key (OOK) modulated light inputs has been demonstrated that harnesses the radiation-pressure gain of a self-sustained electro-opto-mechanical oscillator (EOMO) to render its oscillation amplitude a function of the intensity of light coupled into the oscillator. Unlike previous electronic super-regenerative receivers, this rendition removes the need to periodically quench the oscillation signal, which then simplifies the receiver architecture and increases the attainable receive bit rate. A fully functional receiver with a compact ~90 µm EOMO comprised only of silicon-compatible materials demonstrates successful recovery of a 2 kbps bit stream from an OOK modulated 1550 nm laser input. By removing the need for the expensive III-V compound semiconductor materials often used in conventional optical receivers, this EOMO-based receiver offers a lower cost alternative for sensor network applications.

INTRODUCTION

Radiation pressure-driven optomechanical oscillators (RP-OMO) that harness light energy to produce microwave signals from on-chip micro-devices have proven useful in stand-alone oscillator [1], communications [2], and sensing applications [3]. The addition of electrodes to conventional optomechanical devices allows electrically coupled inputs [4],[5],[6] as well as optical ones that then enable new integrated electro-optomechanical systems where electrical signals modify optical properties [7]. The converse should also be true, where laser light coupled to an electro-optomechanical system might change the electro-mechanical properties of the device, perhaps in a way that allows electrical detection and decoding of optical signals. If possible, this might then enable an optical receiver constructed strictly in silicon compatible materials, i.e., with no need for compound semiconductor photonic devices and the associated cost and technology required to integrate them alongside silicon electronics.

Pursuant to capitalizing on this possibility, and spurred by recent demonstrations of simple low power MEMS radios based on super-regenerative reception [8],[9], this work presents for the first time a fully functional super-regenerative optical receiver based on an electro-opto-mechanical oscillator (EOMO), *cf.* Fig. 1, that detects on-off key (OOK) modulated light input and directly demodulates and recovers input bits in the electrical domain. The key enabler here is the simultaneous use of both electrical and optical input/output (I/O) ports, the former used in the positive feedback loop of a self-sustained electronic oscillator circuit; while the latter used to accept optical inputs that perturb the steady-state oscillation amplitude of the electronic oscillator. Via use of an EOMO constructed of only silicon-compatible materials, this receiver obviates the need for compound semiconductor technology while still providing optical reception commensurate with the needs of massive autonomous sensor networks, for which cost is paramount [10].

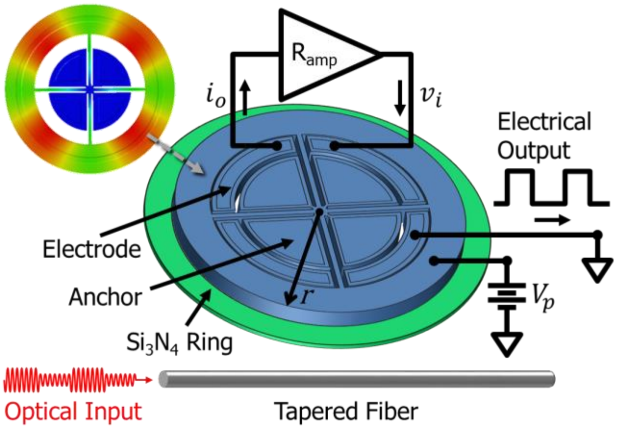

Fig. 1: Perspective-view schematic of the EOMO and basic receiver operation. Here, an electronic amplifier connects to input/output polysilicon electrodes and sustains oscillation. An amplitude modulated optical input couples to the Si_3N_4 ring of the EOMO and changes the output electrical oscillation amplitude, which indicates the received bits.

DEVICE STRUCTURE AND OPERATION

The EOMO illustrated in Fig. 1 comprises a high mechanical Q_m polysilicon inner ring mechanically attached at its outer edge to a concentric high optical Q_o (but comparatively low mechanical Q_m) stoichiometric silicon nitride ring. Four radially symmetric spokes extend from a common central anchor and attach to the inner edge of the polysilicon ring to support the entire structure. The radially symmetric contour mode shape depicted in the inset of Fig. 1 imparts equal and opposite forces along the support beams that cancel on the central anchor point, and thus, generate very little displacement there. This then greatly reduces energy leakage to the substrate, which raises the mechanical Q_m.

Both the polysilicon and silicon nitride rings supply vibrational energy to the composite structure in proportion to their effective masses, defined as $m_{eff} = 2U/\left(\omega_m^2 \cdot \Re(r)\right)$, where U is the total stored energy in the mechanical mode, ω_m the mechanical resonance frequency, and $\Re(r)$ the radial displacement amplitude at radius r. Because it is physically much larger, the polysilicon ring dominates the total effective mass m_{eff}, so its lateral dimensions govern to first order the EOMO’s mechanical resonance frequency. This also means the polysilicon ring contributes a larger portion of the total vibrational energy U in the system while introducing very little loss (because of its high mechanical Q_m). With energy added without additional loss, the composite structure then exhibits a much higher mechanical Q_m

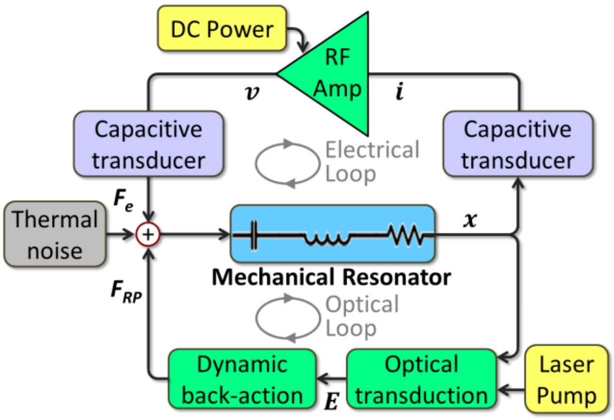

Fig. 2: Super-regenerative optical receiver model. Light received at the proper wavelength forms an additional positive feedback loop, thereby raising the steady-state oscillation amplitude from the no light case (where only the upper branch contributes to the loop gain).

than otherwise provided by a silicon nitride-only ring, as demonstrated in [4]. This high Q_m is key to low power and low phase noise in the present wireless receiver.

Electrical I/O

To enable electrical I/O, four polysilicon electrodes flank the inner edge of the polysilicon ring with 450 nm spacings to form parallel plate capacitors that then realize capacitive-gap transducers. The electrodes anchor to underlying polysilicon interconnects that facilitate signal routing and connection to external electronic circuitry. Exciting the EOMO electrically entails applying a DC bias V_P to the conductive polysilicon ring and an AC voltage v_i to an input electrode, where $V_P \gg v_i$. The voltage difference across the capacitive gap generates a time-varying force that drives the ring into contour mode vibration when it matches the mechanical resonance frequency. The ensuing motion then generates displacement currents across each DC-biased time-varying gap, which can then serve as output signals proportional to displacement or velocity.

Optical I/O

The silicon nitride outer ring enables optical input by accepting laser light from a waveguide—in this case, tapered fiber [11]—brought close enough to evanescently couple the light into to the silicon nitride ring. This ring then serves as a high-Q_o optical cavity that supports whispering gallery mode optical resonances, where the light continuously circulates around the ring outer edges. Ideally, the light would circulate forever. In reality, of course, loss caused by scattering or coupling to nearby objects limits the time light can spend in the ring, which then limits the optical Q_o. Placement of the nitride ring at the outer edge of the structure avoids scattering from the polysilicon material or from coupling with the inner polysilicon electrodes, thereby maximizing the optical Q_o.

Once the ring structure vibrates (via either electrical or optical means to be discussed in the next section), the same fiber that delivered the input light can optically sense the ring motion as a modulation sideband spaced by the ring vibration frequency from the laser carrier. A photodiode can then demodulate the signal to isolate the mechanical resonance.

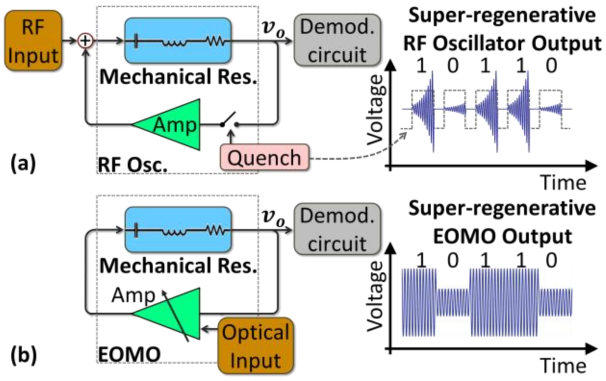

Fig. 3: Comparison of conventional and EOMO-based super-regenerative receivers. (a) Reception of a '1' or a '0' is determined by the speed at which oscillations reach a prescribed threshold value starting from a quenched state. (b) Reception of a '1' or a '0', without quenching, is determined by the amplitude of oscillation, which can switch quickly, greatly increasing the permissible bit data rate.

Self-Sustained Oscillation.

With two I/O modes, the EOMO device of Fig. 1 offers two methods to instigate self-sustained oscillation: electrical or optical. Fig. 2 summarizes the two methods via a simple block diagram with two feedback loops. The electrical method is the same as that used in conventional oscillators [12], where two electrodes (i.e., capacitive-gap transducers) of the EOMO connect to the input and output terminals of an electronic amplifier to create a positive feedback loop with loop gain greater than unity when $A_l = R_{amp}/R_x > 1$. Here, R_{amp} is the transresistance of the amplifier, and

$$R_x = \frac{k}{\omega_m Q_m V_P^2}\left(\frac{\partial C_i}{\partial x}\frac{\partial C_o}{\partial x}\right)^{-1}$$

is the motional resistance between the EOMO electrodes embedded in the loop, where C_i and C_o are the total static capacitances of the input and output transducers, respectively, k is the mechanical stiffness, and x is the resonator displacement. With loop gain greater than unity, regenerative amplification of ring structure's Brownian motion at its resonance frequency eventually leads to sustained oscillation with steady-state amplitude governed by nonlinearities that reduce gain as amplitude increases. The "electrical loop" in Fig. 2 summarizes the operative mechanisms in this mode of self-sustained oscillation.

The optical method, on the other hand, does not require an external amplifier, but rather just a strong enough blue-detuned laser input (or pump) to incite self-sustained optomechanical oscillation, as described in [13]. Here, the field in the high-Q_o cavity builds up to a sizable circulating optical power that generates an outward radial radiation pressure force on the silicon nitride ring. When Brownian motion (again, strongest at the ring mechanical resonance frequency) modulates the optical cavity boundary, it modulates the radiation pressure force, leading to a force at the ring mechanical resonance frequency. When the laser intensity is strong enough, the displacement-to-radiation pressure force transfer function—captured by the "optical

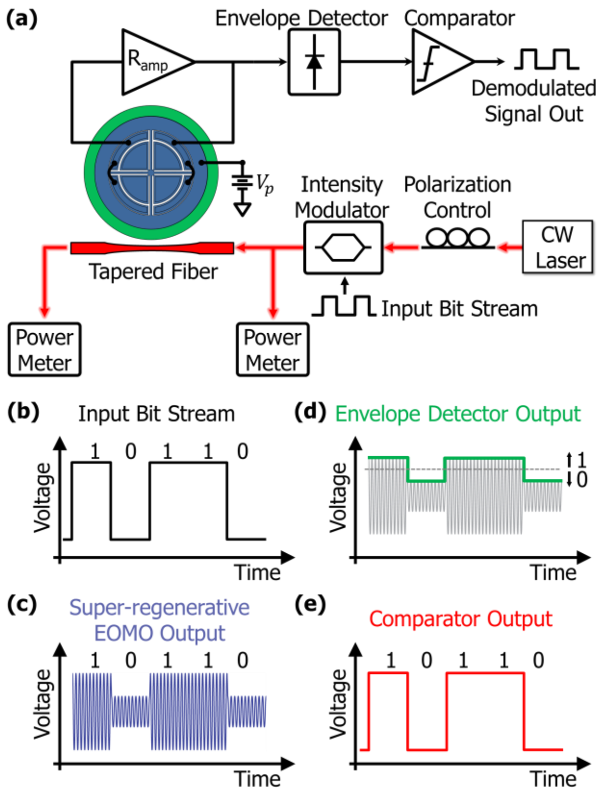

Fig. 4: (a) Pictorial summary of the super-regenerative receiver. An electronic amplifier placed in a positive feedback loop with the EOMO sustains oscillation while a tapered fiber couples the optical field modulated by the input bit stream (b) into the EOMO, changing the amplitude of oscillation (c). An envelope detector measuring the amplitude (d) feeds to a comparator that recovers the data (e).

transduction" and "dynamic back-action" blocks in Fig. 2—contributes sufficient gain to the "optical loop" to achieve a loop gain greater than unity. This then instigates regenerative oscillation growth in the exact same manner as the "electrical loop".

The super-regenerative optical receiver of Fig. 1 employs the gains of both Fig. 2 modes, simultaneously. It specifically uses the electrical mode to instigate and sustain a primary oscillation, and the optical mode to influence the amplitude of the oscillation. To facilitate analysis, Fig. 3(b) condenses the complexity of Fig. 2 into a simpler equivalent block diagram that lumps the electrical and optomechanical gain mechanisms into a single amplifier controlled by the optical input. Here, the stronger the optical input, the larger the amplifier gain. The larger the amplifier gain, the larger the nonlinearity required to limit oscillation growth, and the larger the displacement amplitude needed to generate that nonlinearity. Thus, the steady-state amplitude of the oscillator becomes a direct function of the laser input power, which is the crux behind the present super-regenerative optical receiver.

SUPER-REGENERATIVE OPTICAL RECEIVER

Fig. 3 compares a conventional super-regenerative receiver (a) with the EOMO-based one of this work (b). As shown, both harness the positive feedback loop gain of a closed-loop oscillator to regeneratively, i.e., cycle–by-cycle, achieve an enormous front-end gain capable of detecting tiny received signals. In the former approach, in the absence of an RF signal, the oscillation amplitude rises slowly and gets quenched before reaching a threshold value, which indicates a '0'. On the other hand, in the presence of received RF power, the oscillation amplitude rises quickly past the threshold before quenching, which indicates a '1'. In this case, reception of a '1' or a '0' is determined by the speed at which oscillations reach a prescribed threshold value after starting from a quenched state, where quenching is done once for every bit cycle. In this mode of operation, the bit rate is limited by both the speed at which oscillations grow and the speed at which they can be quenched.

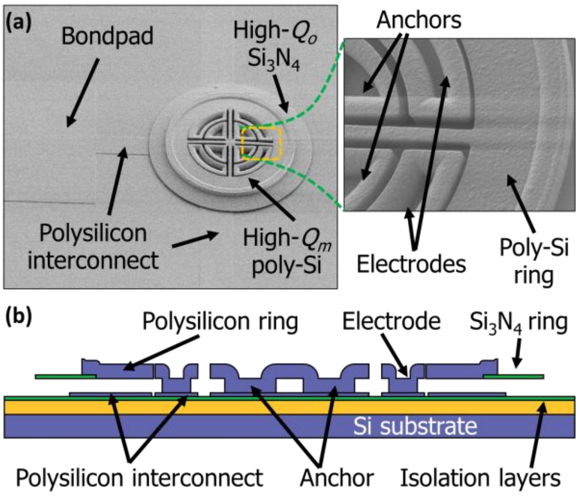

Fig. 5: (a) SEM image and (b) cross-section of the EOMO.

The EOMO-based approach of this work differs in that it does not require quenching of the oscillation. With reference to Fig. 4(a), the EOMO's electrodes are embedded in a positive feedback loop with an electronic amplifier, providing enough gain for oscillation even in the absence of an optical input. An input light that is slightly blue-detuned from the optical resonance wavelength (corresponding to a '1' in OOK) induces radiation pressure, increasing the total force (and the loop gain) applied to the mechanical resonator, and thereby raising the steady-state oscillation amplitude from the no light case (which corresponds to a '0'). The oscillation amplitude thus indicates whether a '1' or a '0' is received. Fig. 4 illustrates this receiver operation by comparing time domain traces at the (c) EOMO amplifier, (d) envelope detector, and (e) comparator outputs, for a given input bit stream (b). Here, since the oscillator merely switches between amplitude states, the time it takes for the amplitude to grow is shorter than growing from zero, so 0-to-1 transitions can be quite fast.

EXPERIMENTAL RESULTS

Fig. 5 presents the SEM and cross-section of the EOMO fabricated via the process of [4] and used to demonstrate optical reception via the setup of Fig. 4(a). The device comprises a polysilicon ring with 30 μm-inner and 40 μm-outer radii physically attached at its outer edge to a 6 μm wide silicon-nitride ring, yielding a 36.9-MHz mechanical resonance frequency with a mechanical Q_m of 15,740.

EOMO and receiver performance measurements used

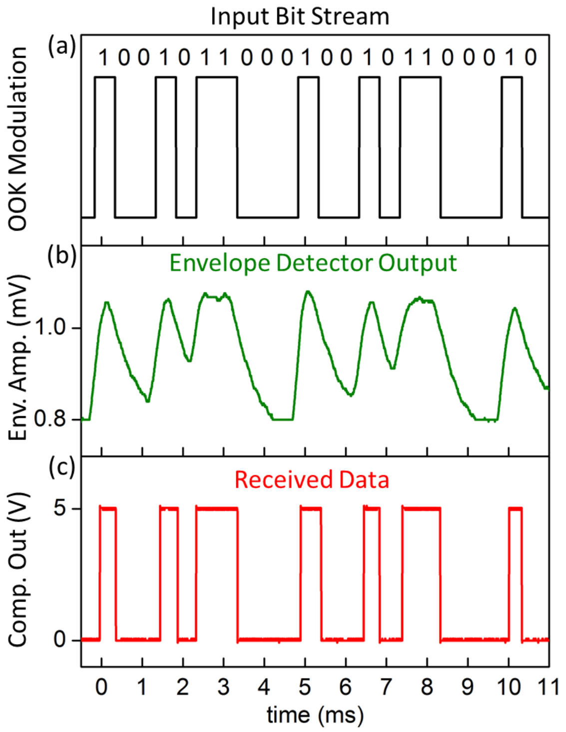

Fig. 6: Measured time-traces illustrating super-regenerative optical receiver operation. (a) Input bit stream modulating a CW laser on resonance, (b) envelope detector output showing the EOMO oscillation amplitude, and (c) output bit stream for a 1 mV threshold from comparator output. The output waveform is identical to the input, as desired, confirming successful wireless optical OOK reception with a 2 kbps data rate.

the custom-built vacuum chamber of [14] in which a sealed probe station provides easy access to device electrodes, and nano-positioning piezo stages provide precise control of optical coupling. To construct the complete optical receiver, the EOMO's electrical ports connect to a sustaining electronic amplifier realized by a Zurich Instruments' HF2LI lock-in unit. Here, the use of a lock-in amplifier provides a simple off-chip implementation with enhanced noise rejection while also conveniently serving as the next stage envelope detector.

Fig. 6 presents measured time-traces confirming receiver operation. Here, an input bit stream modulates the power of a CW 1550 nm laser between 13 μW, indicating a '0', and 750 μW, indicating a '1'. This modulated light input then couples to the EOMO, modulating its radiation pressure gain, thereby modulating the oscillation amplitude. The EOMO's electrical output then feeds an envelope detector that produces the envelope trace in Fig. 6(b). The amplitude trace is then directed to a comparator that produces the output bit stream (Fig. 6(c)) which is identical to the input stream of Fig. 6(a), confirming successful optical OOK reception with a 2 kbps data rate.

CONCLUSIONS

An integrated EOMO has realized a first super-regenerative optical receiver that operates by harnessing the radiation-pressure gain of the EOMO to render its oscillation amplitude a function of the intensity of light coupled into the oscillator. Unlike its RF analogues, this super-regenerative receiver rendition operates without the need to periodically quench the oscillation, and this simplifies the receiver architecture while increasing the attainable receive bit rate. The demonstrated recovery of a 2 kbps bit stream from an OOK modulated 1550 nm laser input by this fully functional EOMO-based optical receiver encourages expansion of this capability to versions that support faster bit rates, perhaps made possible by tweaks to the mechanical and optical *Q*'s of the multi-material device.

By removing the need for the expensive III-V compound semiconductor materials often used in conventional optical receivers, this optical super-regenerative receiver additionally offers a lower cost alternative for sensor network applications. Indeed, the operation modes and mechanisms demonstrated by this EOMO based receiver present one plausible approach to a silicon-compatible single-chip receiver with WDM capability, where multiple devices operating at different wavelengths decode the data simultaneously, allowing channelized optical communications.

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