Energy-Efficient All-Optical Control of Silicon Microring Resonators via the Optical Gradient Force

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Abstract—All-optical control of silicon photonic devices plays a key role in on-chip all-optical computing, switching and signal processing. However, due to the weak intrinsic nonlinear effects of silicon, current integrated devices are limited by high power consumptions. Here, an all-optical controllable optomechanical microring resonator (OMMR) is proposed and fabricated on the silicon platform. Due to the mechanical Kerr effect induced by the optical gradient force (OGF), we realize seamless wavelength tuning over a range of 2.56 nm which is 61% of the free-spectral range, with a high tuning efficiency of 80 GHz/mW. By controlling the pump power, the OMMR indicates three working regions, which are the cutoff region, amplified region and saturate region. Accordingly, this function is similar to a transistor. Furthermore, the dynamic properties of the OMMR are investigated. By analyzing the dynamic responses, we demonstrate that the OMMR is driven by the OGF, rather than other nonlinear effects. The method simplifies the experimental setup, compared with measuring the intrinsic mechanical frequency of the OMMR. This all-silicon device is energy-efficient and compatible with complementary metal-oxide-semiconductor (CMOS) processing. We believe that this work is important for on-chip all-optical signal processing and beneficial to further studies on integrated optomechanics.

Index Terms—Microresonator, optomechanics, optical gradient force, silicon photonics.

I. INTRODUCTION

ANOPHOTONIC circuits have attracted increasing research interest over the past years, because they are the promising platform for realizing densely integrated optics [1], [2], [3], [4], [5], [6]. Conventionally, for the passive silicon photonic devices, they perform the given functions once the structures are designed, which is not conducive to practical applications. Therefore, controllable devices that can be used to actively control light play an important role in photonic integrated circuits [7], [8], [9], [10], [11]. Controllable integrated devices can be realized with traditional electrical methods or with optical methods. Among them, all-optical integrated devices have got increasing attention due to their great potential in applications such as all-optical computing and signal processing [12], [13], [14], [15], [16].

Silicon is a prominent platform for integrated photonic devices due to its advantages of high refractive index, low loss and compatibility with complementary metal-oxide-semiconductor fabrication (CMOS) processing. Therefore, a notable effort has been made to realize the all-optical controllable devices on silicon chip. The thermo-optic effect and $\chi^{(3)}$ nonlinear effect have been used to construct all-optical silicon integrated devices [10], [17]. However, intrinsic nonlinear effects of silicon are usually weak, which causes a high power consumption [18], [19]. High power would lead to some undesired effects, such as two-photon absorption (TPA) which introduces additional insertion loss. Therefore, a strong nonlinear effect is important for practical applications of silicon integrated devices.

Recently, an extremely strong nonlinear effect induced by optical gradient force (OGF) has been studied extensively [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36]. The OGF, which originates from the interaction between optically excited dipoles in a waveguide and the evanescent field of its adjacent waveguide, can cause the mechanical deformation of submicrometer-scale waveguides and changes the effective refractive index ($n_{eff}$) of guided modes, which is called mechanical Kerr effect (MKE), and it could be up to 7 orders of magnitude larger than the conventional Kerr effect of silicon. Furthermore, the OGF can be greatly enhanced by specially designed optomechanical structures based on resonant cavities [31], metamaterials [37], metal-dielectric waveguides [38] and graphene [39]. Due to the strong MKE, it has been demonstrated that the OGF provides an energy-efficient way to achieve the all-optical controllable integrated devices [40], [41], [42], [43], [44], [45], [46], [47], [48].

In this work, we propose and fabricate an all-optical controllable optomechanical microring resonator (OMMR) on the silicon platform. By using the cavity-enhanced MKE, we realize seamless wavelength routing with a tuning efficiency of 80 GHz/mW. Furthermore, by controlling the pump power, the OMMR can work in the cutoff region, amplified region and...
of the resonant mode increases, which causes the
saturation of 200 nm $\lambda_0 = \hbar \omega / \kappa$, where $\kappa$ is the optomechanical coupling coeffi-
cient $[20]$, where $U_{\text{mech}}$ is the intra-cavity stored energy,
and $g$ can
be
in the extra-cavity wavelength. The OGF ($F_{\text{opt}}$) can
be predicted by considering the optical potential energy for the
resonant modes $[41]$, $J=-\partial U/\partial g = U k_{\text{om}} / \lambda$ (1)
where $U$ is the intra-cavity stored energy, $\lambda$ is the wavelength of
light and $k_{\text{om}} = \partial \delta \lambda / \partial g$ is the optomechanical coupling coeffi-
cient $[42]$, where $g = g_0 - x$, $g_0$ is the initial gap before bending,
and $x$ is the deflection at the center point of the suspended
waveguide. The intra-cavity stored energy can be obtained from
the steady-state solution of the cavity field dynamical equation:
$U = \frac{\kappa P_{in}}{[\lambda_0 - \lambda_p]2 \pi c\lambda_p^2 - (\gamma + \kappa)^2 / 4}$ (2)
where $P_{in}$ is the input power in the bus waveguide, $\kappa$ and $\gamma$ are the extrinsic and intrinsic decay rate, respectively, and $\lambda_0$ and $\lambda_p$ are the wavelengths of the cavity resonance and the pump light,
respectively. When the waveguide is deformed, the mechanical
elastic force ($F_{\text{mech}}$) generates, which can be calculated by using
Hooke’s law:
$F_{\text{mech}} = k_{\text{mech}} \cdot x$ (3)
By solving the steady-state equation, the deflection $x$ can be
obtained. Therefore, the corresponding wavelength shift $\delta \lambda$ can be
expressed as:
$\delta \lambda(x) = L_{\text{eff}} \cdot n_{\text{eff}}(x)/m - \lambda_0$ (5)
where $L_{\text{eff}}$ is the effective cavity length of the OMMR and $m$ is
the order of the resonant mode. The relation between $\delta \lambda$ and $x$ is shown in Fig. 1(e).

III. EXPERIMENT RESULTS AND DISCUSSION
The experimental setup is illustrated in Fig. 2. Firstly, an
amplified spontaneous emission (ASE) source whose power
density is around 0.1 mW/nm is injected into the OMMR as
a probe light. Before the light is input into the device under
test (DUT), the polarization beam splitter (PBS) and the
polarization controller (PC) are used to ensure the light to be
TE polarized. The transmission spectrum of the OMMR was
performed by using the optical spectrum analyzer (OSA) with a
resolution of 0.03 nm, as shown in Fig. 3(a). The free-spectral
range (FSR) of the mode family is about 4.2 nm. Since the
deflection of the suspended waveguide will change
by the liquid surface tension, a critical point dryer was used to
remove the remaining liquid.

The electric field component for the fundamental transverse
electric (TE) mode of the suspended waveguide is shown in
Fig. 1(c). When the pump light propagates through the OMMR,
the free-standing waveguide is bent towards the substrate by the
OGF, and $n_{\text{eff}}$ of the resonant mode increases, which causes the
red-shift $\delta \lambda$ of the resonant wavelength. The OGF ($F_{\text{opt}}$) can
be predicted by considering the optical potential energy for the
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cavity modes, the deflection driven by a cavity mode can be used to control the wavelength of an entire mode family. Here, we chose the resonance at $\lambda_{\text{pump}}$ (1554.235 nm) as the pump mode to actuate the free-standing waveguide, and chose the resonance at $\lambda_{\text{probe}}$ (1550.035 nm) as the probe mode to detect the wavelength shift. The loaded quality ($Q$) factors of the pump and probe modes are $1.02 \times 10^4$ and $9.76 \times 10^3$, respectively. With the increased pump power, the probe wavelength is tuned linearly and continuously with a tuning efficiency of $80 \text{ GHz/mW}$, as shown in Fig. 3(b)(blue curve). According to (2), when the resonance wavelength changes, the energy stored in the cavity will change. Therefore, during the tuning process, the pump wavelength needs to increase, which ensures that the energy stored in the cavity remains constant. When the pump power is 4 mW, the tuning range is about 2.56 nm which is 61% of FSR. In principle, it is possible to tune over the entire FSR with a moderate pump power of 6.56 mW. In addition, the thermal effect can also make the wavelength red-shifted. To demonstrate the MKE is dominant in the OMMR, we test another device which is non-corroded on the same chip and only the thermal effect can change the resonance wavelength of the device. The red curve in Fig. 3(a) shows that the tuning efficiency induced by the thermal effect is 12 GHz/mW, which is much smaller than the overall tuning efficiency.

According the above experiments, we demonstrate that the OMMR is an energy-efficient tunable device, then we investigate how it can be used to actively control light. Here, a monochromatic light replaces the ASE source as the probe light, whose wavelength is matched with the probe mode. The probe power is as small as 9 $\mu$W, which is controlled by the variable optical attenuator (VOA). In this case, the probe light hardly causes any nonlinear effect. At the output port, the probe or pump light is filtered out by a tunable bandpass filter (TBPF), then it is collected by a photodetector (PD) and a power meter (PM). From Fig. 3(b), it can be seen that the output power of the probe light is tuned continuously by the pump light, due to the wavelength red-shift induced by the MKE. Obviously, as the pump power increases, the characteristic curve of the probe power goes through three working regions. Firstly, when the pump power is low, the wavelength shift of the probe mode can be ignored due to the weak MKE. In this case, there is no output power, which is similar to the cutoff region of a transistor. Then, as the pump power increases gradually, the wavelength shift of the probe mode also increases, which results in the probe light located at where the slope of the spectrum is the largest. In this case, a small variation of the pump power causes a significant change in the output power of the probe light, which is similar to the amplified region of a transistor. Finally, when the pump power is large enough, the probe light is at the trailing edge of the spectrum where is flat. In this case, the output power increases slowly, which is similar to the saturate region of a transistor. Besides, it can be seen that the transistor-like characteristic curve can be tuned by changing the pump light detuning, $\Delta \lambda = \lambda_{\text{probe}} - \lambda_{\text{pump}}$, where $\lambda_{\text{p}}$ is the pump wavelength. As $\Delta \lambda$ increases, the characteristic curve is gradually optimized, which is mainly manifested in the expansion of the cutoff region, the increase of the slope of the amplified region, and the more distinct saturate region. Therefore, a large detuning is beneficial to obtain a better transistor-like characteristic curve. However, we find that when $\Delta \lambda$ is large enough, the slope of the amplified region is close to infinity and the OMMR cannot work stably in this region. When $\Delta \lambda$ is 0.14 nm and the pump power is high enough, the operating state of the OMMR is repeatedly switched between the cutoff region and the saturate region, and exhibiting the dynamic bistability, as shown in Fig. 4. In order to show the dynamic responses of the OMMR clearly, we directly detect the pump light by using a digital storage oscilloscope (DSO), because of its high power. When the pump power is 225 $\mu$W, the output power is about half of the input power.
and remains constant, as shown in Fig. 4(a), which means the OMMR is deflected by the OGF and works in the steady state. In this case, \( F_{\text{opt}} \) and \( F_{\text{mech}} \) are calculated by (1)–(3), as shown in Fig. 4(f). It can be seen that there is only one intersection between the two curves \( (F_{\text{opt}} \) and \( F_{\text{mech}}) \), which indicates that there is only one steady state in the system. When the pump power is continuously increased to 254 \( \mu \)W, the output power is not stable, as illustrated in Fig. 4(b). On this condition, from the Fig. 4(g), we find that the two curves \( (F_{\text{opt}} \) and \( F_{\text{mech}}) \) intersect at three points, which means there are three steady states in the system. Due to the temperature perturbations, the resonance wavelength of the pump mode has a slight jitter, which causes a small variation of \( F_{\text{opt}} \), but results in a significant change in the deflection of the suspended waveguide. This phenomenon is called “pull-back instability” [21]. Therefore, the suspended waveguide cannot be stabilized in a state for a long time, as well as the output power. Remarkably, although the simulation result in Fig. 4(g) shows that the suspended waveguide can be stabilized in the three states, it only hops between state 3 and state 1, as shown in Fig. 4(b). An analysis is given in the following to explain this phenomenon. When the suspended waveguide passes through state 2, the moving speed is high. Due to the large inertia, it is difficult to stabilize in state 2 for the waveguide. However, when the waveguide reaches state 1 or state 3, the kinetic energy is exhausted and the moving speed is low. Therefore, the suspended waveguide can be stabilized in the state for a short time. Furthermore, when the suspended waveguide moves from one stable state to another, it cannot stop at the steady-state point exactly due to the inertia. However, the suspended waveguide can only keep stable at the steady-state point. Therefore, when the suspended waveguide exceeds the steady-state point due to the inertia, it will be pulled back to the steady-state point, which results in a little change in the output power, as shown in Fig. 4(b)–(d)(red dash boxes). This phenomenon also proves that the suspended waveguide is deformed by the OGF. Furthermore, as shown in Fig. 4(c), (d), it can be seen that the output power remains stable for a longer time with the increase of the pump power. When the pump power increases to 294 \( \mu \)W, the output power is always stable, as shown in Fig. 4(e). In this case, corresponding \( F_{\text{opt}} \) and \( F_{\text{mech}} \) exerted on the suspended waveguide are shown in Fig. 4(j), the number of intersections between the two curves becomes one again.

Then, we chose the transistor-like characteristic curve with the detuning of 0.12 nm to investigate the dynamic properties of the OMMR, as shown in Fig. 5. Here, the pump light is intensity-modulated by an electro-optical modulator (EOM) and the driving signal is generated by an arbitrary waveform generator (AWG). Then, a sinusoidal input signal with the frequency of 10 kHz is obtained, as shown in Fig. 5(b). The maximum and minimum powers of the signal are 125% and 75% of the effective power, respectively, where the effective power is defined as the power of the unmodulated pump light. The probe light is still a constant signal with the power of 9 \( \mu \)W, whose wavelength is aligned with the probe mode. We measure the probe light with the DSO to obtain the output signal. When the effective power of the input signal is 40 \( \mu \)W (970 \( \mu \)W), the OMMR works in the cutoff region (saturate region), compared with the input signal, the amplitude of the output signal is amplified. It should be noted that the probe power is not amplified, because the system is passive.

In addition, the response speed of the OMMR is one of the important dynamic properties. Here, the pump light is modulated as a 50 kHz square-wave signal to characterize the response speed, the result is shown in Fig. 6. Here, the maximum and minimum powers of the input signal are 250 \( \mu \)W and almost 0 \( \mu \)W, respectively, and the detuning \( \Delta \lambda \) is 0.12 nm. In this case,
the thermal effect could be ignored [26]. It can be seen that the rise time (3.71 μs) is much longer than the decay time (1.40 μs). In order to explain this phenomenon, a detailed analysis is given in the following. When the pump power is suddenly increased from 0 μW to 250 μW, the suspended waveguide moves down to the steady state driven by the OGF, and the time spent during this process corresponds to the rise time. According to the above analysis, when the suspended waveguide moves down, there are two forces in opposite directions (F_{opt} and F_{mech}), which are calculated and shown in Fig. 6(b). Therefore, the net force for the downward motion can be calculated, which is shown in Fig. 6(c)(black curve). Besides, when the pump power suddenly disappears, the suspended waveguide cannot remain stable and moves up to the initial position driven by the mechanical elastic force, and the time spent during this process corresponds to the decay time. In this case, only the mechanical elastic force is exerted on the suspended waveguide. The net force for the upward motion is also calculated, as shown in Fig. 6(c)(red curve). Obviously, the net force exerted on the suspended waveguide when it moves up is larger than that when it moves down. Therefore, the average movement velocity of the waveguide is faster when it moves up, which results in a shorter decay time. This phenomenon strongly demonstrates that the suspended waveguide is deformed by the OGF. Remarkably, since air resistances exerted on the waveguide are similar during the two motion processes, they are not considered in the above analysis.

IV. Conclusion

In summary, a low-power-consumption all-optical controllable optomechanical microring resonator has been proposed and fabricated on the silicon platform. Based on the strong mechanical Kerr effect, a high tuning efficiency of 80 GHz/mW has been realized. In addition, the transistor-like function is also achieved. By controlling the pump power, the device works stably in the cutoff region, amplified region, and saturate region, respectively. The dynamic responses of the device are analyzed in detail, and these phenomena demonstrate that the device is driven by the optical gradient force. We believe this work can be utilized in integrated all-optical computing and signal processing.

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