Fully reconfigurable optomechanical add-drop filters

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Abstract: Add-drop filters (ADFs) have important applications in optical communication and information processing. Here we present a broadly tunable add-drop filter based on a double-disk cavity optomechanical system, side-coupled with a pair of tapered fiber waveguides. By changing the cavity-waveguide coupling rates, we investigate the dependence of the through (drop) efficiency on the coupling rates, which agrees well with the theoretical results. By optimizing the cavity-waveguide coupling rates, a drop efficiency of 89% has been achieved. Benefiting from the large optomechanical coupling coefficient of the double-disk microcavity, a tuning range of 8 nm has been realized, which is more than one free spectral range (FSR) of the cavity. This is realized by changing the air gap of the double disk using a fiber tip, which is controlled by a piezoelectrical nanostage, with a required voltage of 7 V. As a result, both the through and drop signals can be resonant with any wavelength within the transparent window of the cavity material, which indicates that the ADF is fully reconfigurable.

I. INTRODUCTION

Whispering-gallery-mode (WGM) microcavities with high quality (Q) factors and small mode volumes can greatly enhance light-matter interactions [1], and therefore have a wide range of applications in quantum optics [2, 3], integrated photonic network [4], optical filters [5–16], cavity optomechanics [17], microscale highly sensitive sensors [18, 19], optical frequency combs [20, 21], etc. Among them, the add-drop filter (ADF) is one of the key elements of optical information processing. The add-drop configuration consists of a high-Q WGM microcavity side-coupled with two waveguides that can ideally filter out all the power from the bus waveguide and transfer it to the other drop waveguide, when the input laser is on resonance with the cavity. This represents a crosstalk of zero and a drop efficiency of 100% [22].

In order to be resonant with any device of the scalable photonic network, the ADF needs to be fully reconfigurable for applications including optical routers, switches, modulators, and miniaturized spectrometers. This requires the WGM cavities in these ADFs to be tunable over a full free spectral range (FSR). This means the WGM cavity can be resonant with any wavelength within the transparent window of the cavity material [23–33]. In addition to the large tuning range, high tuning speed and low power consumption are also required for applications of ADFs in integrated photonic networks. FSR tunable microcavities have many other applications, such as cavity quantum electrodynamics [2, 3] and tunable microlasers [31, 38].

Tuning of the microcavity resonance frequencies is usually realized either by changing the refractive index of the cavity material through thermal-optic effect [23, 24, 39–41], electro-optic effect [42, 43], and free carrier injection [44, 45], or by altering the round-trip length through applying a stress to the cavity [27, 29, 46–50]. However, achieving a full FSR tuning with high speed has proved challenging using these methods. For instance, thermo-optic tuning requires a large temperature increase, which increases the power consumption and affects the filter characteristic due to thermal expansion. In addition, thermal-optic response is usually quite slow [24, 39–41].

Electro-optic tuning and free carrier injection only apply to certain materials, and the realized tuning range are relatively small [42, 45, 51]. Stress tuning to change the cavity circumference usually has a limited tuning range due to the strain limitations of the materials [27, 29, 49].

In recent years, tuning schemes based on strong optomechanical coupling have been demonstrated, including WGM double-disk microcavities [25, 26, 52–55] and two coupled photonic crystal cavities [34, 56, 57]. Wide tuning ranges have been realized, by manipulating the mechanical degrees of freedom in these systems. For example, a tuning range over 32 nm (two FSRS) has been realized using optical gradient forces in a silicon nitride double-disk cavity [25]. More recently, electrical tuning of 9 nm which is more than three FSRS has been demonstrated in a double-disk cavity with interdigitated electrodes fabricated on the disk [26].

Here we demonstrate a fully reconfigurable add-drop filter based on a silica double-disk cavity optomechanical system, side-coupled with two tapered fiber waveguides. We study the relation between the through/drop efficiency and the system losses, including the intrinsic decay rate ($\kappa_i$) of the cavity, and the coupling rates with...
both the bus waveguide ($k_b$) and the drop waveguide ($k_d$). Through optimizing the coupling rates $k_b$ and $k_d$, a drop efficiency as high as 89% and a throughput efficiency of 1.9% has been realized, with a bandwidth of 41.6 GHz for both the through and drop signals. We then tune the cavity resonances by gradually decreasing the air gap of the double disk using a fiber tip. Benefitting from the large optomechanical coupling coefficient (25 GHz/nm) of the double-disk cavity, using an electrical voltage of 7 V has enabled a broad tuning range of around 8 nm, which is more than one FSR of the cavity in 1500 nm. This indicates that the through and drop signals can be resonant with any wavelength in the transparent window of silica, from visible to near infrared.

II. DEVICE DESIGN AND FABRICATION

Figure 1(a) shows a schematic diagram of the double-disk add-drop filter. It consists of an on-chip double disk cavity, side-coupled with a pair of tapered fibers, and a fiber tip on the top disk. The double-disk cavity is composed of two thin silica disks with a small air gap between them. When the input laser is on resonance with the cavity, a Lorentzian lineshaped dip (peak) appears in the transmission spectrum at the throughput (drop) port. Therefore the add-drop filter can realize the functions of band-rejection and band-pass at the throughput and drop ports, respectively. The cavity resonance can be tuned through changing the air gap of the double disk, by pressing the top disk with the fiber tip.

Due to the small air gap between the two disks, their optical modes are strongly coupled, producing symmetric (S) and antisymmetric (AS) modes. An example of the typical optical field distributions of the S (upper panel) and AS (lower panel) modes are shown in Fig. 1(b), obtained by finite element method (FEM) simulation, for a silica double disk with a diameter $d=80$ μm, a thickness $t=400$ nm for each disk, and an air gap $x=250$ nm. It can be seen that the S (AS) mode has a symmetric (antisymmetric) field distribution in the two disks, and a large (zero) field strength in the middle of the gap. It is found that the Q factor of the S mode is generally higher than the AS mode, as the S mode is more confined compared with the AS mode. For instance, the radiation loss dominated Q factors are obtained from the FEM simulation to be $10^{14}$ and $10^4$ for the S and AS modes, respectively.

In order to theoretically analyze the tuning capability of the double-disk cavity, we use FEM to calculate the frequencies of the S and AS fundamental transverse electric (TE) modes, as a function of the air gap ranging from 100 nm to 2 μm. The azimuthal mode numbers of the S and AS modes are $m_S=199$ and $m_{AS}=174$. The simulated frequencies for the S and AS modes are shown in the blue squares and black dots in Fig. 1(c), with the blue and black curves showing their polynomial fitting results. It can be seen that, the frequency of the S (AS) mode becomes higher (lower) with increasing the air gap. The frequencies shift towards opposite directions for the two modes, which can be understood by the change of the effective refractive index ($n_{eff}$) of the modes. For the S mode, more optical field will be distributed in air with a larger air gap, leading to a smaller $n_{eff}$ and a lower frequency. For the AS mode, with the increase of the air gap, more field will be distributed in silica, resulting in a larger $n_{eff}$ and a higher frequency.

By taking a derivative to the fitting curves in Fig. 1(c), we can derive the optomechanical coupling coefficient $|G_{om}| = |d\omega/dx|$ for both the S and AS modes, which quantifies how much the resonance frequency $\omega$ shifts with changing the air gap $x$. Note that the sign of $G_{om}$ is positive (negative) for the S (AS) mode. The $|G_{om}/2\pi|$ for the S and AS modes versus the air gap are shown in the blue and black curves of Fig. 1(d). It is worth noting that the $|G_{om}|$ of the AS mode is larger than that of the S mode, which was also obtained in previous work. From Fig. 1(d) we can see that, the smaller the air gap is, the larger the optomechanical coupling coefficient is. Therefore, a smaller air gap is desired for a larger tuning range. Taking into account the experimental feasibility, we choose the air gap of the double disk to be 250 nm. This gives $|G_{om}/2\pi|$ of 25 GHz/nm and 39 GHz/nm for the S and AS modes, respectively, which are much larger than that of a single WGM cavity of the same diameter. In addition, the double disk has a larger compliant in the out-of-plane motion than the radial motion in a WGM microdisk, which allows tuning with a smaller force. The FSR for the double disk we use is about 6.2 nm in 1500 nm. Therefore, to achieve a tuning range of more than one FSR, the air gap is required to change by more than 32 nm, which can be easily achieved through pressing the top disk using the fiber tip.

In order to further increase the compliance of the double disk to out-of-plane deformation to facilitate tuning, we design an annulus cavity structure supported by four spokes, as shown in the scanning electron microscope (SEM) image in Fig. 1(c), similar to that used in previous work. The thin tethers between the center disk and the spokes can effectively reduce the buckling effects of the disk originating from the clamping region due to built-in internal stress. The inset is a close-up view of the double-disk boundary, showing the air gap of around 250 nm. The fabrication process of the device is shown in Fig. 1(f). We first deposit the SiO$_2$/Si/SiO$_2$ stack layers with thicknesses of 400/250/400 nm onto a silicon wafer, using inductively coupled plasma chemical vapor deposition (ICP-CVD) method. The amorphous silicon between the two silica layers is a sacrificial layer which will be etched away to form a silica double disk. In order to reduce the film stress produced in the deposition processes, the wafer is then annealed for 4 hours at 1000 °C. We then deposit a layer of Chromium (Cr) with a thickness of 70 nm on top of the stack layers through thermal evaporation, and pattern the Cr layer through electron beam lithography (EBL) and lift-off processes,
closely through changing the air gap of the double disk, we scope (OSC). In order to tune the cavity resonances pre-tectors (PDs) separately, and monitored by an oscillocope (OSC). WGM in the double disk. The transmitted light at the control the polarization of the light to match that of the power. A fiber polarization controller (FPC) is used to cal attenuator (VOA) is used to control the input optical the input port of the bus waveguide. A variable opti-tages with a precision of 30 nm. Light from a tunable is precisely controlled using two 3D piezoelectric nanos-disk. The position of the fiber tip is controlled by another 3D piezoelectric nanostage. We fabricate the fiber tip through heating and pulling a standard single mode fiber using a CO₂ laser and then break it until its diameter reaches about 10 μm. Figure b) shows the through (T) and drop (D) efficiencies in 1490-1510 nm range, at the throughput and drop ports, defined as the transmitted and dropped powers normalized by the input power. This wavelength range spans three FSRs of the double disk. It can be seen that several modes appear in one FSR, which exhibit resonant dips in the through signal and peaks in the drop signal.

In order to optimize the drop efficiency, we then study the relation between D and the decay rate of the cavity, including its intrinsic decay rate ω, and its coupling rates ω and ω with the bus and drop waveguides. Starting from the equation of motion for the cavity mode, and using the input-output relation, we can obtain the formula for T, D, and the relation between them, shown on the right of Fig. a). The position of the fiber tip is controlled by another 3D piezoelectric nanostage.

A variable optical attenuator (VOA) is used to control the input optical power. A fiber polarization controller (FPC) is used to control the polarization of the light to match that of the WGM in the double disk. The transmitted light at the throughput and drop ports are detected by two photodetectors (PDs) separately, and monitored by an oscilloscope (OSC). In order to tune the cavity resonances precisely through changing the air gap of the double disk, we use a fiber tip to press the top disk, with its optical image

III. MEASUREMENT AND RESULTS

Figure a) shows the schematic of the experimental measurement setup of the broadly tunable ADF. The double-disk cavity evanescently couples with a pair of tapered fibers, with the top (bottom) one serving as the bus (drop) waveguide. An optical microscope image of the double disk is shown in the middle of Fig. 2(a). The distances between the double disk and each tapered fiber is precisely controlled using two 3D piezoelectric nanostages with a precision of 30 nm. Light from a tunable laser in 1500 nm is coupled into the double disk from the input port of the bus waveguide. A variable optical attenuator (VOA) is used to control the input optical power. A fiber polarization controller (FPC) is used to control the polarization of the light to match that of the WGM in the double disk. The transmitted light at the throughput and drop ports are detected by two photodetectors (PDs) separately, and monitored by an oscilloscope (OSC). In order to tune the cavity resonances precisely through changing the air gap of the double disk, we use a fiber tip to press the top disk, with its optical image

which will be used as the hard mask for etching the stack layers. The SiO₂/Si/SiO₂ layers are then etched using re-active ion etching (RIE), after which the Cr hard mask is removed. Finally, an isotropic XeF₂ etching is performed to etch away both the sacrificial silicon layer and the silicon substrate underneath to suspend the silica double disk.
coupling condition $\kappa_b = \kappa_i + \kappa_d$ at the resonance frequency. Therefore, in order to achieve the highest drop efficiency in experiments, we can reduce the cavity intrinsic decay rate $\kappa_i$ and keep the coupling rates $\kappa_b$ and $\kappa_d$ as large as possible while maintaining the critical coupling condition. We then optimize the drop efficiency for the mode at 1506 nm which has an intrinsic decay rate $\kappa_i/2\pi=2.1$ GHz. We first only couple the bus waveguide with the double disk and maximize $\kappa_b$ by contacting the bus waveguide on the top disk. We then keep the relative position between the bus waveguide and the double disk, and gradually bring the drop waveguide close to the double disk from the other side. Figure 2(c) shows the measured through (red triangles) and drop (blue squares) efficiencies $T$ and $D$, as a function of $\kappa_d/2\pi$. It can be seen that with the increase of $\kappa_d$, the mode experiences coupling conditions from overcoupling ($\kappa_b > \kappa_d + \kappa_i$) to undercoupling ($\kappa_b < \kappa_d + \kappa_i$). As a result, $T$ decreases first and then increases, with a minimum value $T = 1.9\%$ at $\kappa_b/2\pi=18$ GHz and $\kappa_d/2\pi=21.6$ GHz. Correspondingly, the drop efficiency increases first to a maximum value $D = 89\%$, and decreases afterwards. The red and blue curves in Fig. 2(c) are the theoretical results derived from formula (1) and (2), with the decay rates ($\kappa_i$, $\kappa_b$ and $\kappa_d$) obtained through Lorentzian fitting of the transmitted and dropped spectra (Fig. 2(b)). It is noted from the fitted linewidths that $\kappa_b$ is slightly changed during the experiment. The slight deviations between the measured and theoretical values of $D$ could be from the slightly changed $\kappa_i$ due to the additional scattering loss induced by the drop waveguide. We also study the bandwidths $\kappa = \kappa_i + \kappa_b + \kappa_d$ of the band-rejection and band-pass filters, as a function of $\kappa_d/2\pi$, as shown in the red triangles and blue squares of Fig. 2(d), respectively. As expected, the two bandwidths are approximately the same, and both bandwidths increase with $\kappa_d$. The bandwidth is about 41.6 GHz for the maximum drop efficiency of 89%.

In order to realize a broadband tuning of the ADF, we use a fiber tip to press the top disk which can change the air gap of the double disk, while keeping a relatively high drop efficiency. As the position of the fiber tip is gradually lowered by the nanostage, the air gap of the double disk decreases, which shifts the optical res-
FIG. 3. (a) and (b) Through and drop signals in 1490-1510 nm range. From the bottom to the top, the air gap is gradually decreased. Both the through and drop signals show a tuning range of around 8 nm which exceeds the FSR of the double-disk cavity.

The drop efficiency can be further improved by reducing the intrinsic loss of double-disk cavity [14, 15]. The response shape of the filter can be controlled by cascading multiple cavities [10, 13]. While demonstrated using a silica double disk here, our devices can be transferred to integrated systems, such as silicon nitride [25, 53] and silicon on insulator [61]. The fully reconfigurable add-drop filters have a range of potential applications in optical communication and information processing, such as on-chip routing [24, 52], wavelength division multiplexing [7] and microscale spectrometers [62].

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