

Few-MHz bandwidth tunable optical filter based on a fiber-ring resonator

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We present a fiber-ring resonator that realizes an ultranarrowband, high-extinction, low-loss, tunable optical filter. It consists of a pair of commercial variable ratio directional couplers that allow precise adjustment of the filter bandwidth and its on-resonance transmission. This design also grants access to multiple modes of operation, such as a simultaneous band-stop and band-pass filter. Our characterization reveals a bandwidth of less than 2 MHz, together with an extinction exceeding 20 dB. The tunability of the filter properties establishes our device as a versatile platform for selective frequency filtering with sub-natural atomic linewidth resolution.

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I. INTRODUCTION

The use of optical filters is common in most optical applications, allowing the spectral selection or rejection of a particular frequency band and the splitting or combining of light fields of different wavelengths. A plethora of general as well as application-specific commercial filters is readily available and is often engineered to offer high transmittance or reflectance over narrow wavelength ranges [1,2]. However, the achievable bandwidth of commercial filters based on thin-film interference is typically restricted to a few nanometers by inhomogeneities in the thickness of the films [3]. Moreover, a smaller bandwidth generally comes at the cost of a reduced peak transmission/reflection [4]. Among the available alternatives, filters based on periodic optical structures, such as optical gratings or volume Bragg gratings, reduce the bandwidth to several GHz, which is analogously limited by imperfections in the periodic structure inscribed in the bulk material [5]. Filters based on atomic vapors also exhibit bandwidths in the GHz range and are intrinsically matched to atomic transitions, but are fundamentally limited to the specific properties of the atomic medium and by collisional broadening effects [6,7]. Filters based on Fabry-Pérot or ring resonators further improve the key filtering parameters compared with these designs, with commercial devices typically reaching a bandwidth of several MHz [8–11]. For this reason, filter resonators have become key

components in optical communication applications, aiding in the generation, processing, and measurement of optical signals, from laser mode selection and stabilization [12,13] to wavelength division multiplexing [14,15] and spectroscopy [16,17]. Despite their proven efficacy, the performance of modular filter resonators is highly sensitive to the precise alignment of their constituent components. Additionally, free-space light coupling requires careful optimization to ensure accurate mode matching with the cavity. In contrast, fiber-based resonators alleviate these drawbacks by providing high spectral resolution and transmission (or reflection) efficiency while maintaining simple control over the filter characteristics.

Here, we present a simple, robust fiber-ring resonator (FRR) filter design that combines in the same experimental system ultranarrow bandwidth with full tunability in frequency, bandwidth, extinction, and polarization. At the same time, it offers time- and cost-effective fabrication from commercially available components. Its basic design is sketched in Fig. 1. The FRR is coupled to a waveguide that injects light into it and transmits the light field resulting from the interference between the input field and the cavity field. When critically coupled, this realizes a two-port device that acts as a band-stop filter, see Fig. 1(a), blocking resonant and transmitting nonresonant light. When setting a bandwidth of (1.80 ± 0.02) MHz, our filter shows an extinction of (20.5 ± 0.7) dB in the NIR/VIS spectral range, thereby outperforming any commercially available band-stop filter to our knowledge. Coupling a second waveguide to the FRR realizes an add-drop filter that allows one to recover the resonant light and direct it to an independent output. In this add-drop configuration, the filter can also be operated as a band-pass, see Fig. 1(b), and, when setting the bandwidth to (3.00 ± 0.02) MHz, it shows an extinction of (20.1 ± 0.1) dB and a transmission of $(38.4 \pm 0.2)\%$ at

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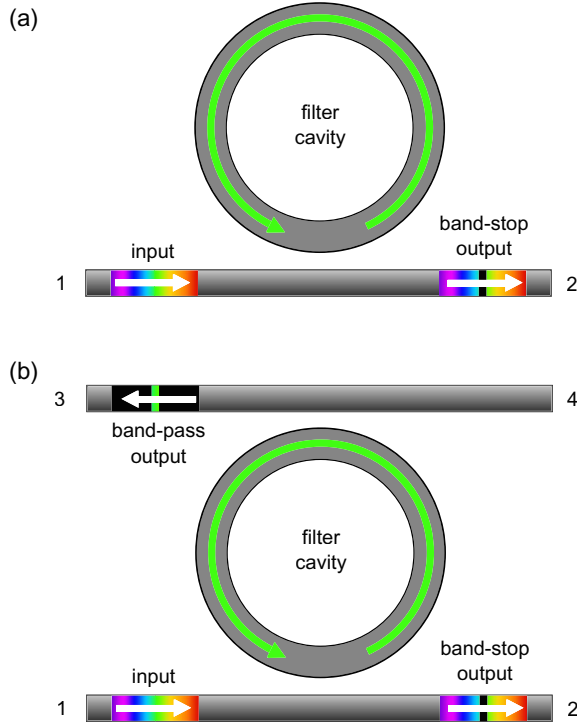


FIG. 1. (a) Filter design operating in a two-port configuration as a band-stop filter. Port 1 is used to inject light, and the band-stop filtered light exits through port 2. (b) Alternatively, the filter can be operated in a four-port add-drop configuration as a simultaneous band-stop and band-pass filter. In this case, the band-pass filtered light exits through port 3, while the band-stop filtered light continues to exit through port 2.

the band-pass output. In the context of quantum optics, these characteristics make our filter compatible with resolving sub-natural linewidth features of laser-cooled atoms and ions as well as dye molecules at cryogenic temperatures. It is thus of great interest, e.g., for analyzing and tailoring the fluorescence light of these quantum emitters [18–20].

II. OPERATION PRINCIPLE

The experimental setup for the characterization of the FRR is schematized in Fig. 2(a), while an actual photo of the device is shown in Appendix A. The FRR is made by splicing together the terminations of two commercially available variable ratio directional couplers (F-CPL-830-N-FA, Newport). Each coupler consists of a pair of single-mode, nonpolarization-maintaining optical fibers. Light can be coupled into and out of the resonator through the bus and drop fiber, respectively. The FRR is placed in a thermally and acoustically insulated box in order to limit the thermal drifts and mechanical vibrations. The optical round-trip length of the FRR can be varied by stretching the fiber with a piezoelectric actuator (PK4FA2H3P2, Thorlabs), which also allows us to actively stabilize the

resonance frequency (see Appendix C for further details). The FRR exhibits two polarization eigenmodes due to the birefringence of the optical fibers. These eigenmodes and their frequency splitting can be freely adjusted using two in-line polarization controllers (CPC900, Thorlabs), which allow one to adjust the fiber birefringence by mechanically compressing and rotating the fiber, respectively. Depending on the desired operation, the FRR can be made polarization-sensitive (if the two eigenmodes are spectrally separated) or polarization-independent (if the two eigenmodes coincide). For our characterization, we set the detuning between the two polarization eigenmodes to approximately 25% of ν_{FSR} , i.e., sufficiently large for the modes not to overlap and sufficiently far from $\nu_{\text{FSR}}/2$, so as to not impede the extinction measurement. For the input light, we use a laser source stabilized at a wavelength of 852 nm and with an output power of about 100 μW . Two photodetectors record the output power at the bus and the drop port, respectively. By tuning the splitting ratio of the variable ratio directional couplers, we can adjust the loss rates of the FRR to the bus port (κ_{bus}) and the drop port (κ_{drop}). The total loss rate of the FRR is thus given by $\kappa = \kappa_0 + \kappa_{\text{bus}} + \kappa_{\text{drop}}$, where κ_0 is its intrinsic loss rate. An optimal point for filter operation is critical coupling, $\kappa_{\text{bus}} = \kappa_0 + \kappa_{\text{drop}}$, at which, regardless of the finesse $\mathcal{F}$ of the resonator, the transmission to the bus port ideally is zero. Figure 2(b) shows the transmission spectra at the bus and at the drop port for various settings of κ under the condition of critical coupling. For $\mathcal{F} \gg 1$, the power transmission coefficients through the bus port and to the drop port are given by the expressions [21]:

$$T_{\text{bus}} = \left| \frac{\kappa_0 + \kappa_{\text{drop}} - \kappa_{\text{bus}} + i\Delta}{\kappa_0 + \kappa_{\text{drop}} + \kappa_{\text{bus}} + i\Delta} \right|^2, \quad (1)$$

$$T_{\text{drop}} = \frac{4\kappa_{\text{drop}}\kappa_{\text{bus}}}{|\kappa_0 + \kappa_{\text{drop}} + \kappa_{\text{bus}} + i\Delta|^2}, \quad (2)$$

where Δ is the detuning from the cavity resonance. As is apparent from Eq. (1), at resonance, $T_{\text{bus}} = 0$ when $\kappa_{\text{bus}} = \kappa_0 + \kappa_{\text{drop}}$.

III. FILTER PERFORMANCE

A. Band-stop configuration

We now study the on-resonance power transmission of the FRR through the bus port when it is operated as a band-stop filter. Here, we keep κ_{drop} fixed at 0 while varying κ_{bus} . For each value of κ_{bus} , we fit an inverted Lorentzian to the transmission spectrum through the bus port. From each fit, the linewidth Γ and the resonance frequency ν_0 of a cavity mode are extracted. The total loss rate is then obtained from the fitted linewidth as $\kappa = \Gamma \times \pi$, while the on-resonance power transmission $T_{\text{bus}}(\nu_0)$ is evaluated by averaging the transmission around the resonance

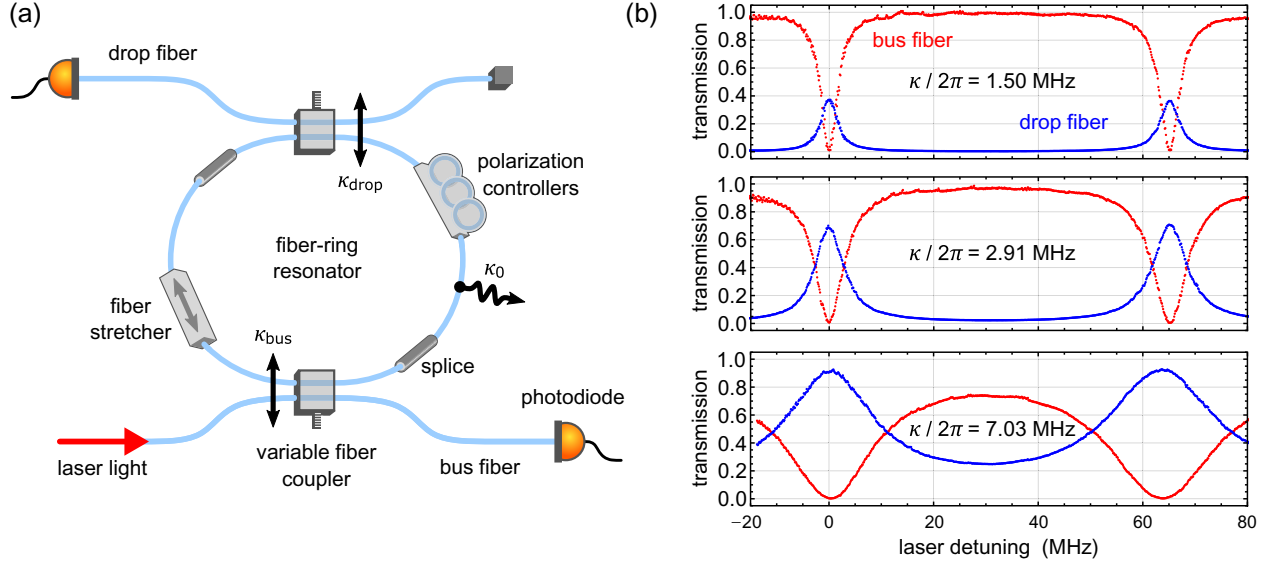


FIG. 2. (a) Add-drop fiber-ring resonator (FRR) filter setup. Laser light ($\lambda \sim 852$ nm), injected into the bus fiber, is coupled into the FRR at a rate κ_{bus} , set by a variable ratio directional coupler. A second variable ratio directional coupler couples light from the FRR to the drop port at a rate κ_{drop} . The transmission in each fiber output is measured using a photodiode. The FRR includes a fiber stretcher that allows us to tune the resonance frequency, as well as polarization controllers to adjust the two polarization eigenmodes and their frequency splitting. The intrinsic loss rate κ_0 of the FRR is dominated by the internal losses of the variable ratio directional couplers. (b) Transmission spectra of the FRR through the bus (red) and drop (blue) ports as a function of the input laser detuning, measured with the input light matching one polarization eigenmode and at the critical coupling point (where the on-resonance transmission at the bus port is minimal). Two adjacent resonator modes are clearly visible and are separated by a free spectral range of $\nu_{\text{FSR}} = (63.37 \pm 0.06)$ MHz. From top to bottom, the filtering bandwidth is increased through adjustment of both κ_{drop} and κ_{bus} (the corresponding setting of κ is indicated), while ensuring that the critical coupling condition is fulfilled.

frequency over a range that is approximately 5% of the linewidth given by the fit, where the error bars are given by the standard deviation of the mean. The resulting values are shown in Fig. 3 together with a fitting curve obtained from Eq. (1) by setting $\kappa_{\text{drop}} = 0$ and $\Delta = 0$. From the value of κ at which the fitted curve reaches its minimum, corresponding to the critical coupling point, we estimate the intrinsic loss rate of the FRR as $\kappa_0/2\pi = (0.449 \pm 0.005)$ MHz. This corresponds to a total filter bandwidth full width at half maximum (FWHM) of (1.80 ± 0.02) MHz and an unloaded finesse of $\mathcal{F}_0 = 70 \pm 1$. The experimental on-resonance transmission measured near critical coupling is $T_{\text{bus}} = (0.9 \pm 0.1)\%$, whereas the transmission in between two resonances is $T_{\text{bus}}(\nu_0 + \nu_{\text{FSR}}/2) = (99.0 \pm 0.1)\%$, corresponding to an extinction of $|10 \log_{10} \frac{T_{\text{bus}}(\nu_0 + \nu_{\text{FSR}}/2)}{T_{\text{bus}}(\nu_0)}| = (20.5 \pm 0.7)$ dB. By combining the round-trip loss inferred from the finesse with the loss estimated from the reduced transmission between adjacent resonances, we obtain an insertion loss at critical coupling of (0.25 ± 0.01) dB. Given that the typical insertion loss of each variable ratio directional coupler specified by the manufacturer is of about 0.1 dB, the overall insertion loss is primarily determined by the couplers, with minor contributions from splices and polarization controllers.

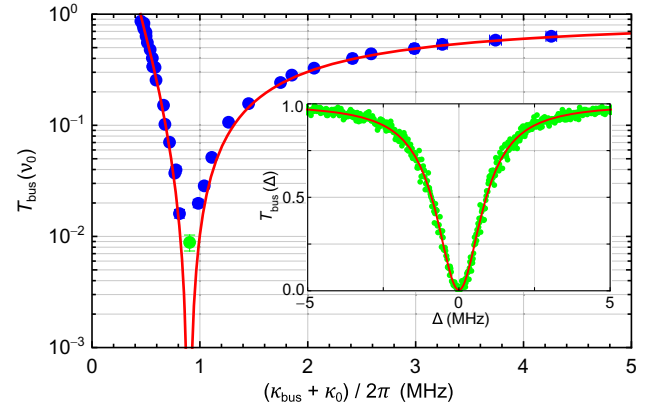


FIG. 3. On-resonance power transmission through the bus port, $T_{\text{bus}}(\nu_0)$, as a function of the loss rate, $\kappa_{\text{bus}} + \kappa_0$, for $\kappa_{\text{drop}} = 0$. For each data point (shown in blue), $\kappa_{\text{bus}} + \kappa_0$ is obtained from a Lorentzian fit to the transmission spectrum around resonance, where the error bars represent the 1σ uncertainty of the fit and are smaller than the size of the data points. The red solid line is a fit according to Eq. (1), with κ_0 as a free parameter. Its minimum indicates the point of critical coupling, where $\kappa_{\text{bus}} = \kappa_0$. The data point closest to critical coupling is highlighted in green, and the corresponding transmission spectrum, together with its Lorentzian fit, is shown in the inset.

To provide a plausible interpretation of the obtained extinction, we calculate the convolution of an ideal Lorentzian resonance at critical coupling with the laser spectrum. Guided by independent linewidth measurements on the laser source, the latter is modeled as a Gaussian with a linewidth (FWHM) of 200 kHz. This yields a predicted extinction of 21.5 dB, which is only marginally higher than the experimentally observed value. Additional factors that may limit the extinction include slight misadjustments of the polarization controllers, leading to residual coupling to the orthogonal polarization eigenmode. These considerations suggest that the measured extinction is primarily limited by the finite laser linewidth and technical imperfections, rather than by intrinsic properties of the FRR.

B. Add-drop configuration

The second use case of the FRR is as a filter in the add-drop configuration. In this case, the drop port causes additional losses, lowering the finesse $\mathcal{F}$ of the FRR. For this reason, Eqs. (1) and (2) need to be generalized in order to take into account the presence of adjacent longitudinal cavity modes (see Appendix B for further details). The generalized expressions were used to fit the transmission spectra at the drop port for various settings of the total loss rate κ , where κ is the fit parameter. Figure 4(a) shows the on-resonance transmission $T_{\text{drop}}(\nu_0)$, whereas Fig. 4(b) shows the extinction $T_{\text{drop}}(\nu_0)/T_{\text{drop}}(\nu_0 + \nu_{\text{FSR}}/2)$ as a function of κ . These values were evaluated from averaging the transmission around ν_0 and around $\nu_0 + \nu_{\text{FSR}}/2$, respectively. Our characterization shows that, when setting $\kappa/2\pi = (1.50 \pm 0.01)$ MHz, i.e., a filter bandwidth (FWHM) of (3.00 ± 0.02) MHz, the FRR has a peak transmission of $(38.4 \pm 0.2)\%$ and a peak-to-valley transmission ratio of about 100/1, i.e., an extinction of (20.1 ± 0.1) dB. From the measured transmitted power, we derive an insertion loss of (0.82 ± 0.03) dB. These values are easily tunable and can be adapted to different requirements, realizing, e.g., a narrower bandwidth and a higher extinction, albeit at the cost of a lower on-resonance transmission through the drop port.

Another significant property of the filter is its broad frequency tunability. Indeed, the maximum displacement of the embedded piezoelectric actuator (around $7 \mu\text{m}$) results in a resonance-frequency shift of the FRR that is well above its free spectral range ν_{FSR} (see Appendix D for further details). Consequently, the filtered frequency can be set arbitrarily within the single-mode transmission range of the fiber. For the fiber used here (HI 780, Corning), this corresponds approximately to wavelengths above 720 nm and below 1000 nm. The filter also shows a very good passive stability, with a maximum passive frequency drift of less than 20 MHz/10 min (see Appendix F for further details).

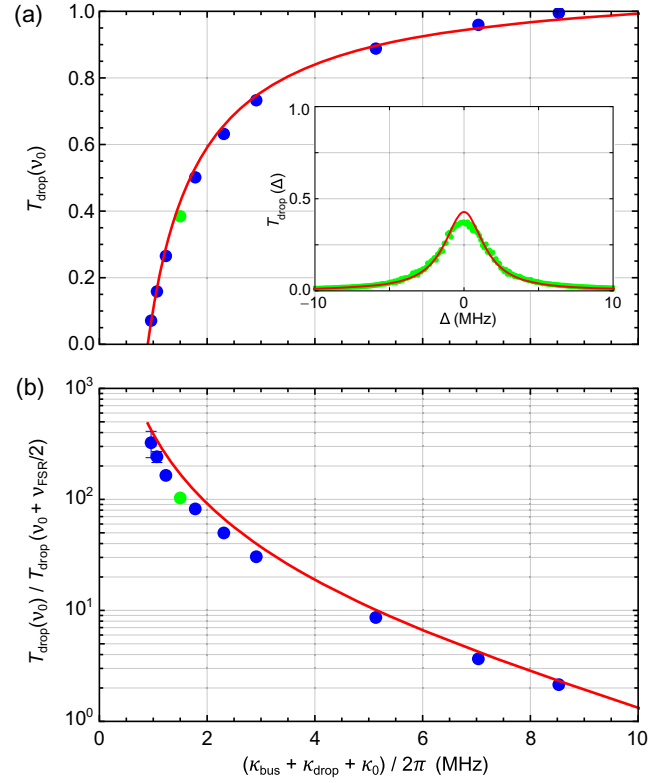


FIG. 4. (a) On-resonance transmission through the drop port, $T_{\text{drop}}(\nu_0)$, as a function of the total loss rate, $\kappa_{\text{bus}} + \kappa_{\text{drop}} + \kappa_0$, where the FRR is always set to critical coupling to the bus port. (b) Extinction of the on-resonance transmission through the drop port as a function of the total loss rate. The total loss rate is evaluated by fitting the generalized multimode cavity model to the transmission spectra, where the error bars represent the 1σ uncertainty of the fit and are smaller than the size of the data points. The transmission is evaluated by averaging the measured data around one resonance frequency and in between two resonances, and the error bars are given by the standard deviation of the mean. The red lines are the predictions of the generalized model. It is evident that increasing the on-resonance transmission comes at the cost of a reduced extinction because of the partial overlap between neighboring cavity modes. A data point selected as representative of the filter performance is highlighted in green, and the corresponding transmission spectrum over one cavity mode, together with the associated fit, is shown in the inset.

IV. CONCLUSION

In conclusion, we have constructed and characterized an optical filter based on a fiber-ring resonator operable in an add-drop configuration, demonstrating its ultranarrowband and high-extinction filtering capability. When operated in both band-stop and band-pass configurations, exemplary properties of our filter are summarized in Table I and compared with those of commercially available ultranarrowband filters and experimental realizations of cavity-based filters. The comparison shows that, although

TABLE I. Comparison of representative ultranarrowband optical filters. The table includes commercially available filters (indicated in italics, with model numbers reported where available), research-grade implementations, and our fiber-ring resonator (FRR) filter in both band-stop and band-pass operation modes. The listed examples cover volume Bragg gratings (VBG), Fabry–Pérot (FP), and FRR-based filters. For filters with tunable bandwidth (BW) or extinction (EXT), when performance ranges are reported in datasheets or in the referenced works, the best-case values are reported. The comparison shows that our filter simultaneously achieves narrow BW, high EXT, and low insertion loss (IL), with performance comparable to the listed alternatives, while preserving full tunability of the main filter characteristics, including BW, EXT, central frequency (ν_0), and polarization (POL).

Model/Reference	Platform	BW (MHz)	EXT (dB)	IL (dB)	ν_0	Tunable properties		
						BW	EXT	POL
BAND-STOP								
<i>OptiGrate</i>	VBG	150000	40	0.46 ^a	✓			
Liu <i>et al.</i> [20]	FP	21	8.2	(N.A.)	✓			
Heebner <i>et al.</i> [22]	FRR	22 ^a	13 ^a	0.36 ^a	✓		✓	
Mik <i>et al.</i> [23]	FRR	3	14 ^a	0.34 ^a				
This work	FRR	1.80(2)	20.5(7)	0.25(1)	✓	✓	✓	✓
BAND-PASS								
<i>WL Photonics WLTF-BA-U</i>	VBG	50000	50	1.5	✓	✓		
<i>Agiltron FOTF</i>	VBG	10000	45	3.0	✓			
<i>Exfo XTA-50</i>	FP	4000	50	4.5	✓	✓		
<i>Thorlabs FPQFA-5</i>	FP	100	30	1.0 ^a	✓			
<i>Quantaser FPE002D</i>	FP	95	36	1.0 ^a	✓			
<i>HJ Optronics FPTF</i>	FP	30	50	3.0	✓			
Mik <i>et al.</i> [23]	FRR	3	14 ^a	0.75 ^a				
This work	FRR	3.00(2)	20.1(1)	0.82(3)	✓	✓	✓	✓

^aValues not explicitly stated but inferred from the available data.

alternative resonator designs might rival or even surpass our system in individual key filter parameters, such as bandwidth and extinction, our solution offers the distinct advantage of achieving, within a single experimental setup, the simultaneous combination of narrow bandwidth, high-extinction, low insertion loss, and full tunability of bandwidth, extinction, central frequency, and polarization. This unique capability makes the FRR filter a compelling choice for fiber-integrated operation.

The filter bandwidth is ultimately limited by the finesse $\mathcal{F}_0$, which in our implementation is dominated by insertion losses of the two variable ratio directional couplers. In the band-pass configuration, $\mathcal{F}_0$ also constrains the peak transmission achievable for a given target bandwidth. Using couplers with lower insertion loss would therefore significantly improve $\mathcal{F}_0$ and, consequently, the filter performance [24]. In principle, the filter bandwidth can also be made narrower or broader by using a FRR of different length. This would change the free spectral range ν_{FSR} , and since the finesse $\mathcal{F}_0$ is almost independent of the FRR length, its linewidth at critical coupling would change by the same amount. The ultranarrow bandwidth makes the filter compatible with resolving spectroscopic features in the MHz-regime. In particular, we recently used it in a band-stop configuration to selectively suppress the coherent emission from a single optically trapped atom, which was weakly driven with near-resonant light [19]. This

enabled the observation of a pronounced change in photon detection statistics of the remaining incoherent emission from antibunching to bunching, with the tunable extinction allowing this transition to be probed gradually as a function of the filter setting. Beyond this specific demonstration, our filter could be used, for example, for spectral cleaning of optical signals in the presence of near-resonant noise, where the combination of ultranarrow bandwidth, high extinction, and full tunability allows unwanted spectral and polarization components to be efficiently suppressed. In general, our filter can be used in situations that require narrow-linewidth resonances and that also call for ease of mode-matching and an alignment-free design. Our filter design thus represents a viable alternative to current established resonator-based filters in a broader range of applications beyond quantum optics [23,25–27].

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are publicly available [28].

APPENDIX A: HOUSING OF THE FRR

Figure 5 shows a photo of the contents of the insulating box. It consists of three nested layers: an inner wooden box, an intermediate polystyrene box, and an outer wooden box. Two circular apertures are made on opposite sides of the box to allow access for the input and output optical fibers, as well as for the electrical cabling connected to the piezoelectric actuator. The upper lid of the box can be easily removed, as shown in the photo, to allow adjustment of the frequency splitting between the two polarization eigenmodes. In contrast, the two variable ratio directional couplers can be tuned from outside the enclosure using a screwdriver through dedicated access holes (not visible in the photo), thus eliminating the need to open the box during this adjustment. To enhance mechanical stability, all individual components are rigidly fixed using screws, and the optical fibers are secured to an optical board with adhesive tape. In addition, a rubber mat is placed between the outer insulating box and the underlying optical bench (not visible in the photo).

APPENDIX B: RESONATOR TRANSMISSION FOR HIGH LOSSES

When the finesse of the FRR is so low that the total loss rate κ is no longer much smaller than the free spectral range ν_{FSR} , consecutive cavity modes are not



FIG. 5. Photograph of the insulating box hosting the FRR filter, with the upper lid removed. The main constituting components are labeled in red: variable ratio directional couplers at the bus (a) and drop (b) port, polarization controllers (c), (d), piezoelectric stretcher (e), and splices along the fiber-ring path (f), (g). The unlabeled components are not part of the filter setup.

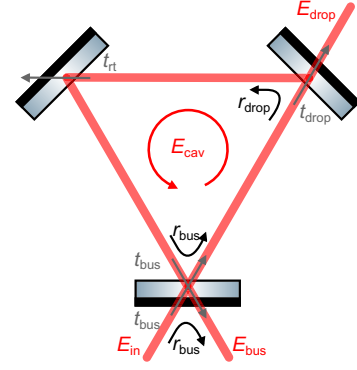


FIG. 6. Sketch of the ring resonator model under consideration, featuring the notation used in the text.

fully separated in the transmission spectrum. This occurs in particular when operating the FRR as a band-pass filter, where the addition of the drop fiber lowers the finesse and the equations used for the characterization in the main text need to be generalized to account for this effect. The system can be modeled as a ring resonator consisting of three semi-reflective mirrors, one per each loss channel (bus, drop, and intrinsic losses), as shown in Fig. 6.

We denote r_{bus} and t_{bus} as the amplitude reflection and transmission coefficients at the bus port, r_{drop} and t_{drop} as the amplitude reflection and transmission coefficients at the drop port, and t_{rt} as the intrinsic amplitude transmission coefficient per round trip. E_{in} , E_{bus} , E_{drop} , and E_{cav} indicate the electric fields at the input port, the bus port, the drop port, and the cavity, respectively. A self-consistent calculation of the fields yields:

$$T_{\text{bus}} = \left| \frac{E_{\text{bus}}}{E_{\text{in}}} \right|^2 = \left| \frac{\frac{-i\Delta}{e^{\nu_{\text{FSR}}}} r_{\text{drop}} t_{\text{rt}} - r_{\text{bus}}}{\frac{-i\Delta}{e^{\nu_{\text{FSR}}}} r_{\text{bus}} r_{\text{drop}} t_{\text{rt}} - 1} \right|^2, \quad (\text{B1})$$

$$T_{\text{drop}} = \left| \frac{E_{\text{drop}}}{E_{\text{in}}} \right|^2 = \left| \frac{t_{\text{bus}} t_{\text{drop}}}{-e^{\frac{i\Delta}{\nu_{\text{FSR}}}} r_{\text{bus}} r_{\text{drop}} t_{\text{rt}} + 1} \right|^2, \quad (\text{B2})$$

where T_{bus} and T_{drop} are the power transmission at the bus and the drop port, respectively. The introduced coefficients are related to the loss rates κ_0 , κ_{bus} , and κ_{drop} defined in the main text by: $t_{\text{rt}} = \sqrt{1 - 2\kappa_0/\nu_{\text{FSR}}}$, $r_{\text{bus}} = \sqrt{1 - 2\kappa_{\text{bus}}/\nu_{\text{FSR}}}$, and $r_{\text{drop}} = \sqrt{1 - 2\kappa_{\text{drop}}/\nu_{\text{FSR}}}$. In addition, the relation $r_{\text{bus}}^2 + t_{\text{bus}}^2 = r_{\text{drop}}^2 + t_{\text{drop}}^2 = 1$ holds. As a consequence, the critical coupling is reached when $r_{\text{bus}} = r_{\text{drop}} t_{\text{rt}}$ or, in terms of the loss rates:

$$\kappa_{\text{bus}} = \frac{-2\kappa_0 \kappa_{\text{drop}} + \kappa_0 \nu_{\text{FSR}} + \kappa_{\text{drop}} \nu_{\text{FSR}}}{\nu_{\text{FSR}}} \quad (\text{B3})$$

In order to infer the loss rate κ corresponding to the data points shown in the main text for the characterization of the filter in the band-pass configuration, we fitted the

respective transmission spectra with Eq. (B2) while fixing κ_0 to the value obtained from the analysis of the filter in the band-stop configuration, fixing ν_{FSR} to the value obtained from an independent measurement, imposing the condition in Eq. (B3), and leaving solely κ as a free parameter of the fit. We note that Eqs. (B1) and (B2) reduce to the equations used in the main text in the limiting case $\kappa \ll \nu_{\text{FSR}}$.

APPENDIX C: DESCRIPTION OF THE PIEZO STRETCHER

For the measurements reported in the main text, active frequency stabilization of the FRR was not implemented, as its passive stability was more than sufficient over the acquisition time of the transmission spectra. Nevertheless, active stabilization can be readily achieved using the dedicated fiber stretcher described below, whose components are illustrated in Fig. 7.

A discrete piezoelectric stack with a through-hole (PK4FA2H3P2, Thorlabs) is bonded to a rigid L-shaped bracket mount, with the fiber fed concentrically through both. Prior to mounting, the protective coating of the fiber is removed over a length exceeding that of the L-bracket (approximately 10 cm). One end of the bare fiber is glued to a cylindrical adapter attached to the piezo stack, preventing direct contact between the glue and the piezoelectric element. The opposite end is glued to a V-groove plate mounted on a compact linear translation stage (M-DS25-X, Newport Corporation), where a micrometer screw allows manual prestraining of the fiber. Except for the fiber, all mechanical components are rigidly connected, and the L-shaped bracket is fixed to the optical bench with dedicated screws. By applying a control voltage to the piezoelectric stack, its elongation induces a controlled axial stretching of the fiber between the two bonding points. This enables precise tuning and, if desired, active stabilization of the FRR resonance frequency with respect to an external frequency reference.

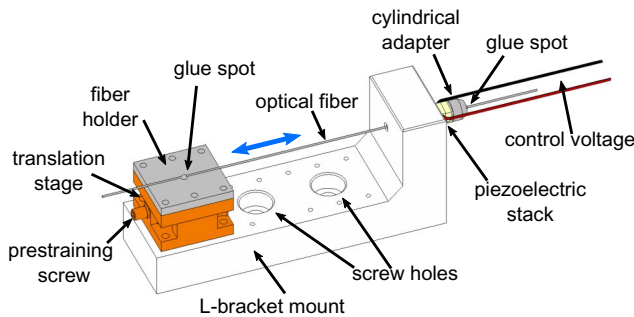


FIG. 7. Schematic illustration of the piezoelectric fiber stretcher used to control the length of the FRR and, consequently, the filtered central frequency. The individual components are indicated by black arrows, while the blue arrow denotes the direction of fiber elongation.

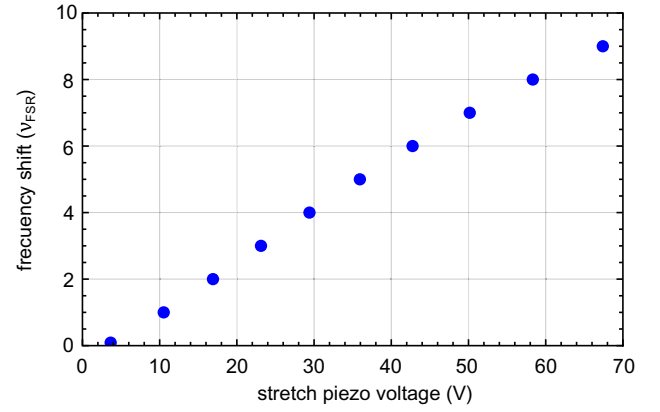


FIG. 8. Frequency shift of the FRR in units of ν_{FSR} as a function of the voltage applied to the piezo stretcher. The error bars, which result from the uncertainty of the voltage controller of the piezo and the uncertainty of the Lorentzian fit used to determine the resonance position, are smaller than the size of the data points.

APPENDIX D: TUNABILITY OF THE FRR VIA THE PIEZO STRETCHER

To characterize the frequency tunability of the filter, we operate it in the add-drop configuration ($\kappa_{\text{drop}} > 0$) close to the critical coupling point, send frequency-stabilized light through it, match the light polarization to one of the two FRR polarization eigenmodes, and monitor the transmission at the drop port. At the same time, we linearly scan the FRR length by varying the voltage applied to the stretching piezoelectric actuator from 0 to 70 V, that is about half its maximum operating voltage. From the number of transmission maxima observed throughout the scan, each separated by ν_{FSR} , we calculate the corresponding frequency shift, as shown in Fig. 8. In the selected scan range, we observe a frequency shift over more than 9 ν_{FSR} , verifying that we can tune the resonance frequency to any arbitrary frequency value.

APPENDIX E: FREQUENCY RESPONSE OF THE PIEZO STRETCHER

To characterize the frequency response of the piezoelectric stretcher, we operate the filter in the band-stop configuration close to the critical coupling point and the input laser frequency is adjusted to reach approximately 50% transmission. A sinusoidal modulation of the control voltage is applied to the piezoelectric stack, with an amplitude much smaller than the difference between 0% and 100% transmission in order to remain in the linear regime of the FRR transmission vs the applied piezo voltage. We record the time-dependent transmission through the bus port, and we fit it with a sinusoidal function, from which we extract its amplitude and phase. In Fig. 9, we show the resulting Bode plot as a function of the applied modulation frequency. The frequency response

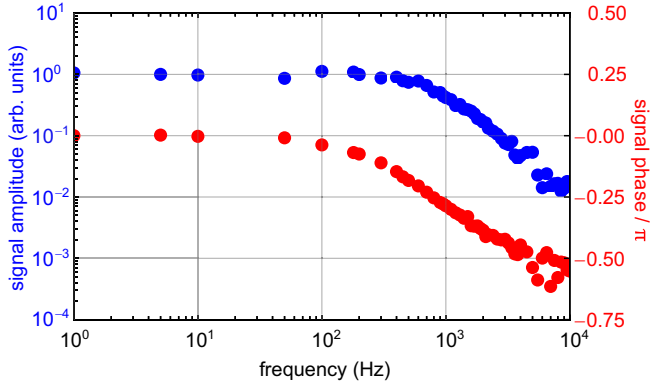


FIG. 9. Bode plot characterizing the frequency response of the FRR. In blue is shown the signal amplitude, in red the signal phase. The error bars, derived from the sinusoidal fit, are much smaller than the size of the data points.

of the fiber stretcher is constant up to a cut-off, after which the signal amplitude exponentially decays and the signal phase linearly decreases to $-\pi$. The value of the cut-off frequency (approximately 1 kHz) is in good agreement with theoretical expectations based on the electrical properties of the system: the capacitance of the piezo stack (560 nF), the applied offset voltage (approximately 50 V), and the available driving current (12 mA). A stabilization protocol with a characteristic frequency well below the cut-off can easily be applied to the filter with standard methods.

APPENDIX F: PASSIVE STABILITY OF THE FRR

In order to characterize the passive stability of the filter, we set it close to critical coupling in the band-stop configuration without frequency stabilization and acquired one transmission spectrum per minute over approximately one week, from which the drift of the resonance frequency of one of its modes was estimated. At the same time, we recorded the temperature inside the insulating box with a thermocouple. The two measurement records are shown superposed in Fig. 10(a). The observed nonmonotonous drift of the resonance frequency shows correlations with the temperature, likely due to variations in the refractive index of the optical fiber [25]. We attribute the time shift between the temperature variations and the response of the FRR to the different thermal time constants of the optical board (where the FRR was placed) and the wooden wall of the insulating box (where the thermocouple was placed).

In Fig. 10(b), we show the time derivative of the resonance-frequency drift. The data acquisition of the individual transmission spectra is affected by large readout noise. To reduce its effect and obtain a more accurate result, each data point represents the average drift over a 10-min interval. Based on this analysis, the maximum resonance-frequency drift rate is found to be below

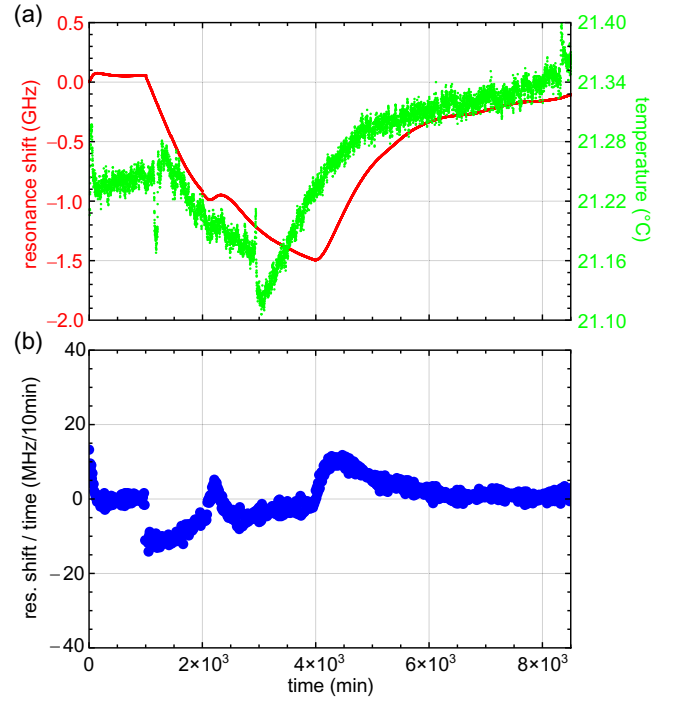


FIG. 10. Long-term frequency drift of the FRR. (a) The red curve shows the resonance frequency of one of the FRR modes, measured once per minute. The green dots show the simultaneously measured temperature in the insulating box. (b) Inferred rate of frequency drift of the FRR.

20 MHz/10 min, which can be effectively counteracted by the active stabilization and thermal isolation of our setup. As a reference, we recently used a sample-and-hold method to stabilize the resonance frequency of our FRR every 5 s [19]. This ensures that the maximum drift is at most 2% of the filter bandwidth (FWHM). In addition, before the measurement, the frequency splitting of the two polarization eigenmodes of the FRR was set to approximately 25% of ν_{FSR} to monitor the drift of their spectral separation. Over a measurement period of about one week, the frequency splitting varied in a range between 11.2 and 13.4 MHz, corresponding to roughly 3% of ν_{FSR} , which indicates long-term stability of the polarization control.

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