High-Order Tunable Filters Based on a Chain of Coupled Crystalline Whispering Gallery-Mode Resonators

Anatoliy A. Savchenkov, Vladimir S. Ilchenko, Andrey B. Matsko, and Lute Maleki

Abstract—**We demonstrate experimentally a tunable third-order optical filter fabricated from the three voltage-controlled lithium niobate whispering gallery-mode resonators. The filter operates at 1550 nm with 30-MHz bandwidth and can be electrooptically tuned by 12 GHz in the linear regime with approximately 80-MHz/V tuning rate. With this filter, we have demonstrated 6-dB fiber-to-fiber insertion loss and 30-ns tuning speed, limited by the resonator buildup time.**

Index Terms—**High-order optical filters, nonlinear optics, optical filters, optical resonators, Q factor, tunable filters, whispering gallery-mode (WGM) resonators.**

MICROWAVE filters with narrow bandwidth and wide tunability are crucial to the realization of advanced communications and radar schemes. The narrow bandwidth naturally allows increased channel capacity in a communications band, while tunability provides spectral diversity and increased efficiency. Unfortunately, microwave filters that also have a bandpass with a flat top and high sidemode rejection cannot simultaneously provide narrow bandwidths (high-quality (Q) factor) and wide tunability. Typical high-Q filters in the 10-GHz regime have bandwidths in the range of a few megahertz, with cavity filters providing the highest Qs. These filters, nevertheless, have either a fixed center frequency, or are tunable through bandwidths that represent a minor fraction of the center frequency. The high-Q filters also introduce several decibels of insertion loss in microwave circuits; the typical insertion loss for a multipole filter with a few megahertz linewidth at 10-GHz center frequency is about 10 dB. It should also be mentioned that the quality of microwave filters generally degrades as the center frequency increases above several tens of gigahertz.

Photonics filters based on optical whispering gallery-mode (WGM) resonators have been devised to address the shortcomings of microwave filters. Multipole high-Q filters based on cascaded WGM microresonators fabricated with silica have been demonstrated allowing compact packages and robust performance at 10–100-GHz bandwidths and corresponding optical Qs on the order of $10^5 - 10^4$ [1]–[6], and are in fact commercially available. These filters provide passbands with a flat top and sharp skirts, suitable for high performance applications. Since the microwave signals in photonic systems are sidebands of an optical carrier, these filters, in principle, can be used at any microwave frequency, providing the same characteristics throughout the band, from 1 to 100 GHz and higher.

While delivering high optical Qs and desirable passband spectra, optical WGM filters based on silica ring resonators are limited in their microwave Q and in availability of convenient tuning technique. Mechanical trimming of WGMs with applied strain [7]–[9] and temperature tuning [10] have been previously used. Though the mechanical as well as temperature tuning ranges are large, e.g., on the order of a few to several tens of nanometers for thermal tuning, these methods are not very convenient for many applications because of small tuning speeds and low tuning accuracy. The tuning accuracy is especially important for high-Q resonators with narrow filter bandwidth. An all-optical tunable filter design based on discontinuity-assisted ring resonators that does not have the above-mentioned disadvantages has also been proposed theoretically [11], but, to our knowledge, no experimental implementation of the configuration has been reported.

A recent technique for WGM resonance tuning was demonstrated using microring resonators with a photosensitive coating [12]. Another approach for trimming the frequency of microresonators exploits the photosensitivity of germanate silica glass [13]. A second-order optical filter based on two coupled resonators, one of which was tunable, was experimentally realized for optical high-Q (10^8) WGM germanate glass resonators [14]. Recently, fabrication of optical WGM resonators with lithium niobate [15] has led to the demonstration of a high-Q microwave filter with a linewidth of about 10 MHz and a tuning range in excess of 10 GHz [16]. Unfortunately, the Lorentzian lineshape of the filter function associated with a single microresonator represents a severe limitation for its application in many systems that require large sidemode rejection, in addition to a narrow bandpass and a large tuning range.

In this letter, we report on the realization of a miniature resonant electrooptically tunable third-order Butterworth filter. The filter is based on three WGM disc cavities fabricated from a commercially available lithium niobate wafer (see Fig. 1). The filter, operating at the 1550-nm wavelength, has approximately 30-MHz bandwidth and can be tuned in the range of ±12 GHz by applying dc voltage of ±150 V to an electrode.

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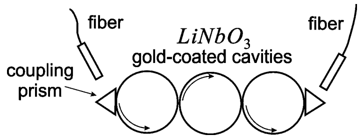

Fig. 1. Scheme of a third-order tunable optical filter made of gold-coated lithium niobate discs.

The free spectral range (FSR) of each resonator is approximately 13.3 GHz, and, therefore, the filter may be tuned practically at any optical frequency in the transparency range of lithium niobate. To clarify this statement, let us consider a single resonator first. If we are able to tune its spectrum by the FSR frequency, the resonator spectrum would overlap with itself, which means that it is always possible to find and to shift a resonator mode to coincide with an arbitrary external signal frequency. We do not need to use the same mode for the filtering. Now, if we consider several interacting resonators, and we are able to tune the frequency of a mode of the smallest resonator (the largest FSR) by the FSR value, and hence, the modes of the other resonators by values exceeding their FSR, then we are able to reconstruct the high-order filter passband at any given frequency. This is the case reported in this letter.

We note the following distinctive features/advantages of this filter over the existing ones: 1) agile tunability accompanied by a high-order filter function; 2) narrow linewidth; and 3) low fiber-to-fiber loss. The combination of the three features makes our filter a unique device for a wide range of applications in optics and microwave photonics.

Tunable single-resonator filters are characterized by their finesse which is equal to the ratio of the filter's FSR and the bandwidth. Our three-resonator filter has a significantly more sparse spectrum as compared with a stand alone WGM resonator. This feature is due to the so-called Vernier effect [17] and is similar to the coupled fiber-ring resonators [18], [19] which are noted for a rare spectrum due to a single sequence of modes. Effective finesse of our system is very large ($F > 10^6$) as the effective FSR exceeds a terahertz, though we were unable to measure it accurately because of insufficient laser tunability. The tuning speed of our filter is limited by the wiring layout and is approximately equal to 10 ns, while the actual shifting time of the spectrum is determined by the filter's bandwidth and does not exceed 30 ns.

A schematic diagram of the tunable filter configuration is shown in Fig. 1. The Z-cut disk resonators have a 3.3-mm diameter and 50-μm thickness. The resonators were cut out from metalized crystalline preforms. Each resonator's perimeter edge was hand polished in the toroidal shape with a 40-μm curvature radius. The repeatable value of the loaded Q factor of the main sequence of the resonator modes we used was $Q = 8 \times 10^6$ (the observed maximum was $Q = 2 \times 10^8$), which corresponds to 30-MHz bandwidth of the mode. We studied several disks with nearly identical characteristics.

The resonators were arranged in the horizontal direction with homemade flex manipulators. There was no need in a vertical adjustment because the surface of the stage the resonators were placed on was optically polished and the resonators were polished as well and all had the same thickness (with nanometer accuracy). The gaps between the resonators and between the prisms and the resonators were 50–100 nm, which corresponds to the evanescent field scale. We did not measure the gaps directly but adjusted them to have the appropriate system response.

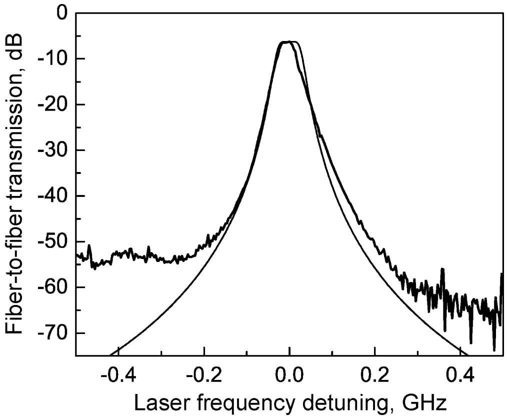

Fig. 2. Transmission curve of the filter and its fit with Butterworth profile function $\gamma^6/[(\nu - \nu_0)^6 + \gamma^6]$, where $\gamma = 29$ MHz, ν_0 determines the center of the filter function and primarily depends on the resonators' geometrical dimensions. Voltages applied to the resonators vary near zero in 10-V range to properly adjust frequencies of each individual resonator and construct the collective filter function as shown.

Light was sent into, and retrieved out of, the resonator via coupling diamond prisms. The repeatable value of fiber-to-fiber insertion loss, primarily due to inefficient coupling to the resonator modes, was approximately 6 dB across the entire cascaded structure. The maximum transmission was obtained when light was resonant with the resonators' modes. We believe that antireflection coating of the coupling prisms or use of special gratings placed on high-index fibers may reduce the losses significantly. Tuning of the filter was realized by applying a voltage to the top and bottom electrodes fabricated with gold. The gold coating is absent on the central part of the resonator perimeter edge where WGMs are localized.

The differences in the size of the resonators is rather important in the fabrication of the device. Our aim was to produce spectral lines in all three resonators with a similar width to allow the realization of a complex line structure. If resonances of the interacting cavities have different widths, then as they are tuned to approach each other, the height of the narrower resonance will simply track the shape of the wider ones, which is of no use for the filter application. The size of each resonator is important since cavities of similar size have similar optical coupling and similar FSR, so similar optical modes with the same efficiency may be excited in each of them. The performance of our filter demonstrates that we are able to fabricate similar resonators with approximately the same parameters.

Fig. 2 depicts the spectrum obtained in the experiment with three cascaded $LiNbO_3$ resonators. To highlight the filter performance, we have also plotted the theoretical third-order Butterworth fit of the curve. Obviously, the three-cavity filter has much faster rolloff compared with the Lorentzian line of the same full-width at half-maximum. On the other hand, the filter function does not look exactly like a third-order one because of small differences between the cavity Q factors and dimensions of the resonators.

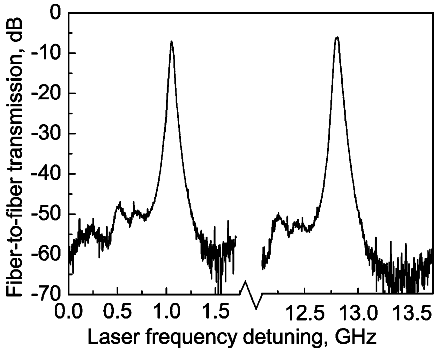

Fig. 3. Transmission curve of the filter and the same curve reconstructed at an approximately 12-GHz frequency shift from the initial transmission curve center ν_0. Optimum voltages applied to the discs are different for all the resonators and are scaled from 100 to 150 V.

The experimentally measured electrooptic tuning of the filter's spectral response, and tuning of the center frequency with an applied voltage, is shown in Fig. 3. The filter exhibits a linear voltage dependence in the ±150-V tuning range, i.e., the total tuning span exceeds the FSR of the resonator. Changing the tuning voltage from zero to 10 V shifted the spectrum of the filter by 1.3–0.8 GHz for transverse-magnetic (TM) mode polarization.

Let us now compare the properties of this filter with the theoretical predictions. The maximum frequency shift of the transverse-electric (TE) and TM modes may be found from [20]

$$\Delta\nu_{\mathrm{TE}} = \nu_0 \frac{n_e^2}{2} r_{33} E_Z, \quad \Delta\nu_{\mathrm{TM}} = \nu_0 \frac{n_o^2}{2} r_{13} E_Z \qquad (1)$$

where $\nu_0 = 2 \times 10^{14}$ Hz is the carrier frequency of the laser, $r_{33} = 31$ pm/V and $r_{13} = 10$ pm/V are the electrooptic constants, $n_e = 2.28$ and $n_o = 2.2$ are the refractive indexes of $\mathrm{LiNbO_3}$, E_Z is the amplitude of the electric field applied along the cavity axis. We used the TM modes because they have larger Q factors than TE modes. If the Q factor is not very important, it is better to use the TE modes because their electrooptic shifts are three times as large as those of TM modes for the same values of the applied voltage. Numerical estimations obtained with (1) are in good agreement with the experimental measurements.

Theoretically, $\Delta\nu_{\mathrm{TE}}$ and $\Delta\nu_{\mathrm{TM}}$ do not depend on the resonator properties and are related to the fundamental limitations of optical resonator-based high-speed electrooptic modulators [21]. The different results for different resonators measured in our experiment stems from the imperfections of the cavity metal coatings as well as a partial destruction of the coating during the polishing procedure.

In conclusion, we have demonstrated an electrically controllable optical filter consisting of three coupled ultrahigh-Q $\mathrm{LiNbO_3}$ resonators. Such a system is basically a tunable third-order filter with a sharp rolloff. The technique used in this work may also be expanded to produce other tunable complex filter functions with various desired line shapes. Such filters enable a large channel density in communications networks, and in many advanced architectures of radio-frequency photonics systems. The application of the filter in photonics is especially promising because it can operate at any microwave frequency superimposed with an optical carrier. Our experimental results are in agreement with the theory.

REFERENCES

[1] B. E. Little, S. T. Chu, H. A. Haus, J. Foresi, and J. P. Laine, "Microring resonator channel dropping filters," *J. Lightw. Technol.*, vol. 15, pp. 998–1005, Jun. 1997.
[2] J. V. Hryniewicz, P. P. Absil, B. E. Little, R. A. Wilson, and P.-T. Ho, "Higher order filter response in coupled microring resonators," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 320–322, Mar. 2000.
[3] S. T. Chu, B. E. Little, W. Pan, T. Kaneko, and Y. Kukubun, "Cascaded microring resonators for crosstalk reduction and spectrum cleanup in add-drop filters," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1423–1425, Nov. 1999.
[4] ——, "Second-order filter response from parallel coupled glass microring resonators," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1426–1428, Nov. 1999.
[5] K. Djordjev, S. J. Choi, S. J. Choi, and P. D. Dapkus, "Microdisk tunable resonant filters and switches," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 828–830, Jun. 2002.
[6] O. Schwelb and I. Frigyes, "Vernier operation of series coupled optical microring resonator filters," *Microwave Opt. Technol. Lett.*, vol. 39, pp. 258–261, 2003.
[7] A. L. Huston and J. D. Eversole, "Strain-sensitive elastic scattering from cylinders," *Opt. Lett.*, vol. 18, pp. 1104–1106, 1993.
[8] V. S. Ilchenko, P. S. Volikov, V. L. Velichansky, F. Treussart, V. Lefevre-Seguin, J.-M. Raimond, and S. Haroche, "Strain-tunable high-Q optical microsphere resonator," *Opt. Commun.*, vol. 145, pp. 86–90, 1998.
[9] W. von Klitzing, R. Long, V. S. Ilchenko, J. Hare, and V. Lefevre-Seguin, "Frequency tuning of the whispering-gallery modes of silica microspheres for cavity quantum electrodynamics and spectroscopy," *Opt. Lett.*, vol. 26, pp. 166–168, 2001.
[10] H. C. Tapalian, J. P. Laine, and P. A. Lane, "Thermooptical switches using coated microsphere resonators," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 1118–1120, Aug. 2002.
[11] O. Schwelb and I. Frigyes, "All-optical tunable filters built with discontinuity-assisted ring resonators," *J. Lightw. Technol.*, vol. 19, pp. 380–386, Mar. 2001.
[12] S. T. Chu, W. Pan, S. Sato, T. Kaneko, B. E. Little, and Y. Kokubun, "Wavelength trimming of a microring resonator filter by means of a UV sensitive polymer overlay," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 688–690, Jun. 1999.
[13] A. A. Savchenkov, V. S. Ilchenko, T. Handley, and L. Maleki, "Ultraviolet-assisted frequency trimming of optical microsphere resonators," *Opt. Lett.*, vol. 28, pp. 649–650, 2003.
[14] ——, "Second-order filter response with series-coupled silica microresonators," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 543–544, Apr. 2003.
[15] V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, and L. Maleki, "Nonlinear optics and crystalline whispering gallery mode cavities," *Phys. Rev. Lett.*, vol. 92, p. 043 903, 2004.
[16] ——, "Tunable filter based on whispering gallery modes," *Electron. Lett.*, vol. 39, pp. 389–391, 2003.
[17] G. Griffel, "Vernier effect in asymmetrical ring resonator arrays," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1642–1644, Dec. 2000.
[18] P. Urquhart, "Compound optical-fiber-based resonators," *J. Opt. Soc. Amer. A*, vol. 5, pp. 803–812, 1988.
[19] K. Oda, N. Takato, and H. Toba, "Wide-FSR waveguide double-ring resonator for optical FDM transmission system," *J. Lightw. Technol.*, vol. 9, pp. 728–736, Jun. 1991.
[20] R. W. Boyd, *Nonlinear Optics*. New York: Academic, 1992.
[21] J.-L. Gheorma and R. M. Osgood, "Fundamental limitations of optical resonator based high-speed EO modulators," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 795–797, Jun. 2002.