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Published in:
Optics Letters

Published: 01/03/2010

Document Version:
Post-print, also known as Accepted Author Manuscript, Peer-reviewed or Author Final version

Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1364/OL.35.000769

Publication details:
Wang, Z., Chiang, K. S., & Liu, Q. (2010). Microwave photonic filter based on circulating a cladding mode in a fiber ring resonator. *Optics Letters*, *35*(5), 769-771. https://doi.org/10.1364/OL.35.000769

Citing this paper
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Microwave photonic filter based on circulating a cladding mode in a fiber ring resonator

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We propose a microwave photonic filter based on circulating a cladding mode in a fiber ring resonator, where the cladding mode is injected into and extracted from the resonator with a pair of matching long-period fiber gratings (LPFGs). The filter has a compact configuration and allows the frequency spacing and the notch depth to be tuned easily. The use of LPFGs also provides the capability of wavelength selection and tuning. Using a standard single-mode fiber and a pair of CO_2-laser written LPFGs, we demonstrate a filter with a frequency spacing of ~1.3 GHz and a notch depth of ~17 dB. Our experimental results agree well with theoretical calculations. © 2009 Optical Society of America

OCIS codes: 060.5625, 230.5750, 060.2340.

Optical fiber ring resonators have extensive applications in microwave and radio-frequency (RF) signal processing as filters [1,2]. A fiber ring resonator can be constructed by simply connecting an output port of a single-mode fiber directional coupler (DC) to its input port [3,4]. It functions as a notch filter, where the notch depth depends on the matching between the coupling ratio of the DC and the loss in the fiber loop. Because a commercial DC has a fixed coupling ratio, it is not easy to tune the notch depth of the filter. Nevertheless, one may adjust the notch depth by introducing bending loss in the fiber loop [5], but bending can increase the signal loss and there is also a limit that the fiber can be bent because of the finite size of the fiber loop. The loop length of a conventional fiber ring resonator is typically several tens of centimeters or longer (restricted mainly by the size of the DC), which limits the frequency spacing to several hundred MHz. On the other hand, extremely compact fiber ring resonators can be formed with strongly tapered fibers, namely microfibers [6]. Because of their very small size (of the order of ~1 mm in diameter), however, microfiber resonators have a typical frequency spacing of several ten GHz. In this paper, we propose a new fiber ring resonator, which can fill the frequency spacing gap between a conventional fiber ring resonator and a microfiber resonator and offer many advantageous features.

Our fiber ring resonator is constructed with a bare fiber loop, where the light wave propagating in the loop is a cladding mode instead of the guided core mode. The cladding mode is injected into and extracted from the resonator with a pair of matching long-period fiber gratings (LPFGs) and the cladding mode is coupled in and out the fiber loop through evanescent-field coupling between two parallel sections of the fiber [7]. The size of the fiber loop can be made small by allowing distributed optical coupling along the same bare fiber by coiling the fiber, as in the case of a microfiber resonator. Therefore, it is possible to achieve much wider frequency spacing (GHz and above), compared with a conventional fiber ring resonator. The use of LPFGs also allows wavelength selection and tuning, which is important for wavelength-division multiplexing (WDM) applications. In this paper, we demonstrate the principle of the cladding-mode fiber ring resonator and its features, and discuss the factors that affect the performance of the device.

Figure 1(a) shows a simple implementation of the proposed fiber ring resonator. It consists of a fiber loop formed with a bare fiber (a fiber with its jacket removed) and two matching LPFGs. The LPFG at the input end (LPFG 1) couples the guided core mode into a cladding mode and the LPFG at the output end (LPFG 2) does the opposite. The bare fiber loops back to itself with two sections placed closely together in a groove coated with a low-index silicone polydimethylsiloxane (PDMS), where evanescent-field coupling between the cladding modes of the two fiber sections takes place. The notch depth of the filter response can be controlled easily by changing the strength of evanescent-field coupling between the two parallel fiber sections. It is also easy to adjust the length of the fiber loop and hence the frequency spacing of the filter by moving the fiber through the groove with a translator. Moreover, the operation wavelength of the resonator can be changed by tuning the resonance wavelength of the LPFGs (e.g., by changing the temperature or the surrounding index of the LPFGs) or using LPFGs designed for a different wavelength. The wavelength-selective property of the filter can be explored for WDM applications, where one wavelength channel is selected for signal processing and the others are allowed to pass through.

Figure 1(b) is a block diagram of the experimental setup for the characterization of the fiber ring resonator. Light emitted from a low-coherence laser is intensity-modulated with an electro-optic modulator driven by an RF generator. The RF-modulated light is amplified by an erbium-doped fiber amplifier and launched into the fiber ring resonator. The output signal is detected with a photodetector and analyzed with a signal analyzer (EXA, N9010A). The cladding mode that carries the RF signal circulates around the fiber loop with a portion of its power coupled out the loop every time when it passes the evanescent-field coupling region.

The output of the resonator is the sum of all the recirculating RF signals tapped from the fiber loop. Following the approach detailed in Ref. 4 and assuming incoherent light, we derive the normalized RF transmission of the filter as

$$\frac{P_4}{P_1} = (1-\gamma_0)^2 \left[\frac{K^2 + \sigma^4 (1-2K)^2 + 2K\sigma^2 (1-2K)\cos(\beta L)}{1+\sigma^4 K^2 - 2\sigma^2 K \cos(\beta L)} \right], \tag{1}$$

where P_1 and P_4 are the powers of the input and output RF signals, respectively; K is the power coupling efficiency (between Port 1 and 4 or between Port 2 and 3 in Fig. 1); L is the loop length; $\beta = 2\pi \upsilon_{\mathrm{RF}} n_{\mathrm{eff}} / c$ is the phase constant of the RF signal in the fiber with υ_{RF} the RF frequency, n_{eff} the effective index of the cladding mode, and c the speed of light in vacuum; and $\sigma^2 = (1-\gamma_0)\exp(-2\alpha_0 L)$ is the overall optical power loss over one round-trip of the fiber loop with $2\alpha_0$ and γ_0 being the optical attenuation coefficient of the cladding mode propagating in the loop and the loss induced in the groove, respectively. According to Eq. (1), a series of notches appears at the RF frequencies that satisfy the phase resonance condition $\cos(\beta L) = -1$ and the RF output power at the notch frequencies is zero under the condition $K = \sigma^2 / (1+2\sigma^2)$. Therefore, the notch depth depends on both the coupling efficiency and the optical loss. In our case, the notch depth can be optimized by changing the coupling coefficient in the evanescent-field coupling region. From Eq. (1), we derive the 3-dB bandwidth of the filter $\Delta\upsilon$ as

$$\Delta\upsilon = \frac{FSR}{\pi} \arccos\left[\frac{\left(1+\sigma^4 K^2\right) C - K^2 - \sigma^4 \left(1-2K\right)^2}{2\sigma^2 K C - 2K\sigma^2 \left(2K-1\right)} \right], \tag{2}$$

where $C = 0.5[K + \sigma^2 (1-2K)]^2 / (1-\sigma^2 K)^2$ and $FSR = c/(n_{\mathrm{eff}} L)$ is the free spectral range, namely, the frequency spacing, which is inversely proportional to the loop length.

The fiber used for forming the loop was a standard telecommunication single-mode fiber with a cladding diameter of 125 μm. The two LPFGs were written in B-Ge co-doped fibers (Fibercore, PS1250/1500) by a CO_2 laser [8]. The use of a B-Ge co-doped fiber allows the grating to be inscribed in the core so that the coupled cladding mode can maintain perfect axial symmetry, and thus provides polarization-independent operation [8]. The pitch and the number of periods of the two gratings were 334 μm and 50, respectively. The resonance wavelengths of LPFG 1 and LPFG 2 were 1552.9 nm and 1547.9 nm, respectively, the corresponding contrasts were 24.0 dB and 20.0 dB, respectively, and the 3-dB bandwidths were 50 nm and 51 nm, respectively. The coupled cladding mode was the LP_{08} mode. The transmission spectra of the gratings are shown in Fig. 2. The laser source emitted at 1548.0 nm with a power of 1.1 mW. The RF power delivered from the RF generator was 15 dBm.

In the first experiment, the fiber ring resonator was constructed according to the configuration shown in Fig. 1(a). The lengths of the fiber loop and the groove were 362 mm and 57.5 mm, respectively. The evanescent-field coupling efficiency was adjusted by changing the separation between the two parallel sections of the fiber in air [7]. The RF frequency response is shown in Fig. 3. The measured frequency spacing and the notch depth were 569.7 MHz and ~19 dB, respectively. The optical loss in the fiber loop was measured to be ~5 dB, which was mainly due to the bending loss of the LP_{08} cladding mode and any spurious power transfer from the LP_{08} mode to other cladding modes. The results calculated from Eq. (1) with $K = 0.28$, $\sigma = 0.68$, $n_{\mathrm{eff}} = 1.444$ (for pure silica), and $L = 362$ mm match the experimental results well. We were able to shorten the loop length continuously by more than 200 mm with a resolution of ~1 mm by translating the fiber across the groove, which corresponded to a continuous tuning of the frequency spacing from ~570 MHz to ~1.3 GHz. The resonator allows both coarse and fine tuning of the frequency spacing.

In the second experiment, we placed the entire fiber loop in a circular groove with a diameter of 50.9 mm to form a compact self-coupling configuration, as shown in Fig. 4. The evanescent-field coupling region was curved and followed the shape of the loop. With this configuration, the fiber loop was shortened to 160 mm. We applied an index-matching liquid (with an index of 1.377 at 1550 nm) to a section of the self-coupling region to control the coupling coefficient [7] and hence the notch depth. The RF response of the filter is shown in Fig. 5. The frequency spacing and the notch depth were ~1.3 GHz and ~17 dB, respectively. The measured optical loss in the fiber loop was ~3 dB. The calculated results with $K = 0.23$, $\sigma = 0.81$, $n_{\mathrm{eff}} = 1.444$, and $L = 160$ mm agree well with the experimental data.

The frequency spacing depends on the length of the fiber loop. The minimum size of the loop (limited by the bending loss of the cladding mode) is of the order of several centimeters, which corresponds to a maximum frequency spacing of a few GHz. A further reduction of the loop size should be possible by using a fiber with a smaller cladding diameter, such as an etched fiber. As shown in Fig. 2, the two LPFGs used in our experiments are not perfectly matched and the rejection at the operation wavelength is smaller than 20 dB, which means that a small amount of the guided core mode is launched into the resonator and picked up at the output. This can give rise to additional intensity noises and limit the notch depth. The performance of the filter can be improved by using better matched LPFGs with a higher rejection at the operation wavelength. CO_2-laser written LPFGs with a 60-dB rejection have been demonstrated [9].

In conclusion, we propose a microwave photonic filter based on circulating a cladding mode in a fiber ring resonator, where optical coupling is achieved by cladding-mode evanescent-field coupling and the cladding mode is excited and extracted with a pair of matching LPFGs. The filter offers many desirable features, including a compact configuration, a tunable coupling coefficient, an adjustable loop length, and wavelength selectivity. These features allow more flexible and accurate fiber resonator designs for microwave/RF filtering applications. Using a standard single-mode fiber and a pair of CO_2-written LPFGs, we demonstrate a filter with a loop length of 160 mm, which gives a frequency spacing of ~1.3 GHz and a notch depth of ~17 dB. The frequency spacing is limited by the size of the fiber loop and could be further increased by using a smaller loop formed with a fiber that has a smaller cladding diameter, such as an etched fiber. The performance of the filter could be further improved by using better matched LPFGs.

The authors wish to thank K. P. Lor, Nelson S. C. Chan, C. Zhang, Y. Liu, and Robust Lai for technical assistance. This research was supported by a grant from the Research Grants Council of the Hong Kong SAR, China [Project No. CityU 111907].

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Figure Captions:

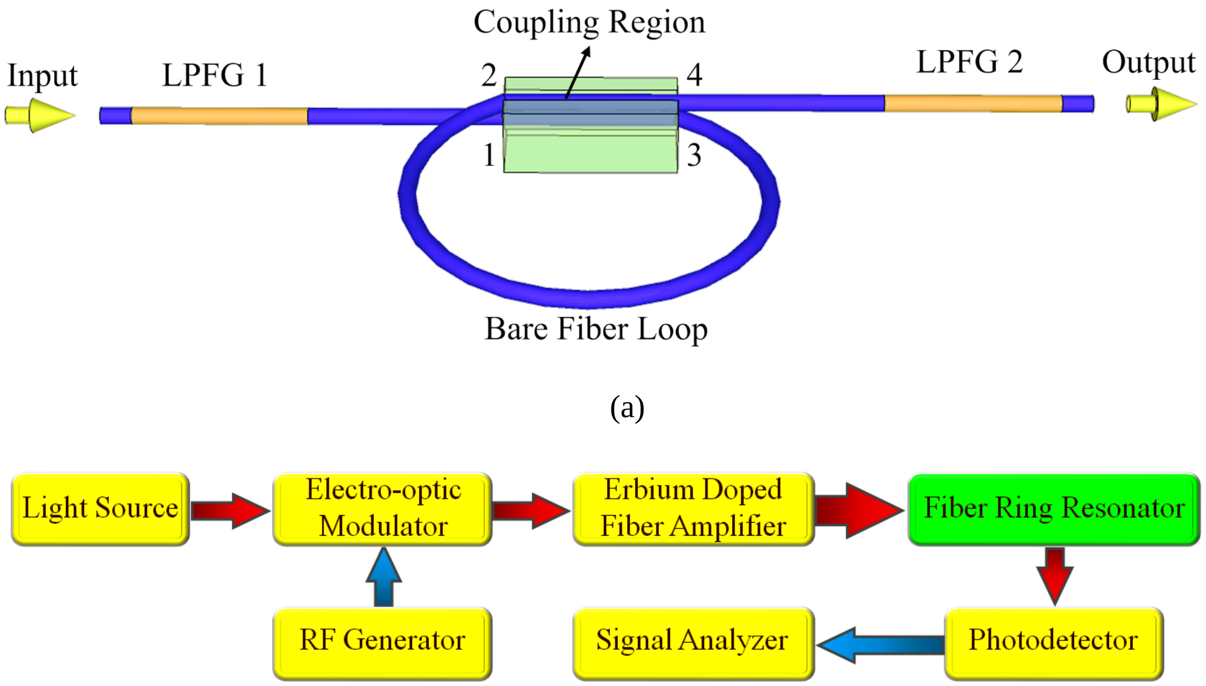
Fig. 1. (a) Schematic diagram of the proposed fiber ring resonator and (b) block diagram of the experimental setup for the characterization of the resonator.

Fig. 2. Transmission spectra of the two LPFGs used in the experiments.

Fig. 3. Measured (dots) and calculated (solid) normalized frequency responses of a microwave photonic filter that has a loop length of 362 mm.

Fig. 4. A more compact cladding-mode fiber ring resonator, where the entire fiber loop is placed in a groove with part of it coiled up to achieve self-coupling.

Fig. 5. Measured (dots) and calculated (solid) normalized frequency responses of a microwave photonic filter that has a loop length of 160 mm.



(a)

(b)

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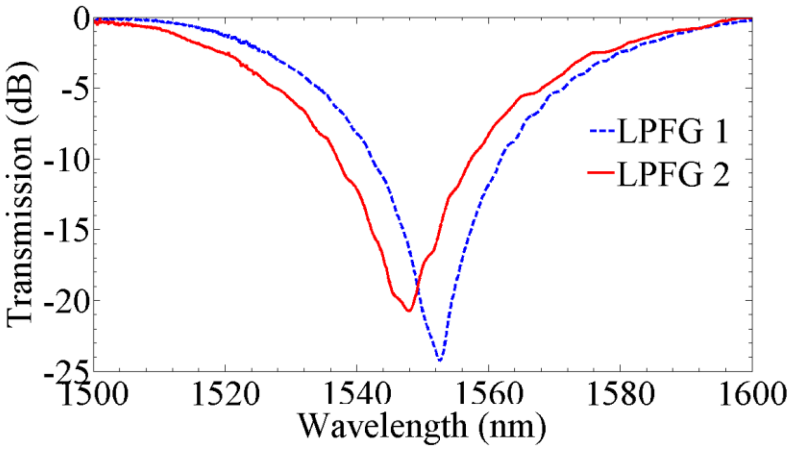

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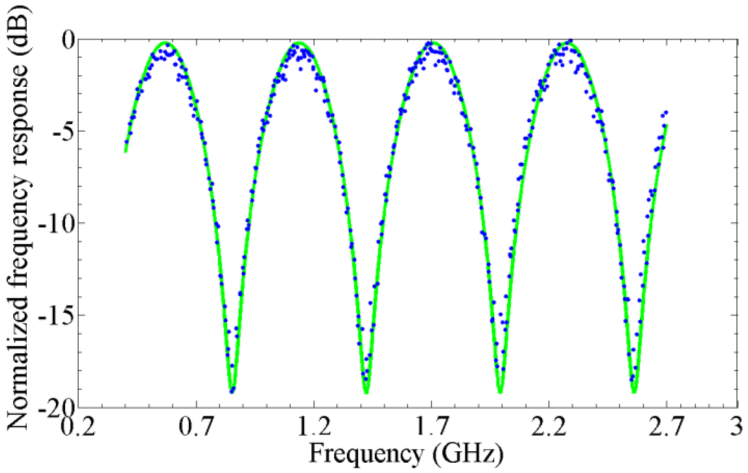

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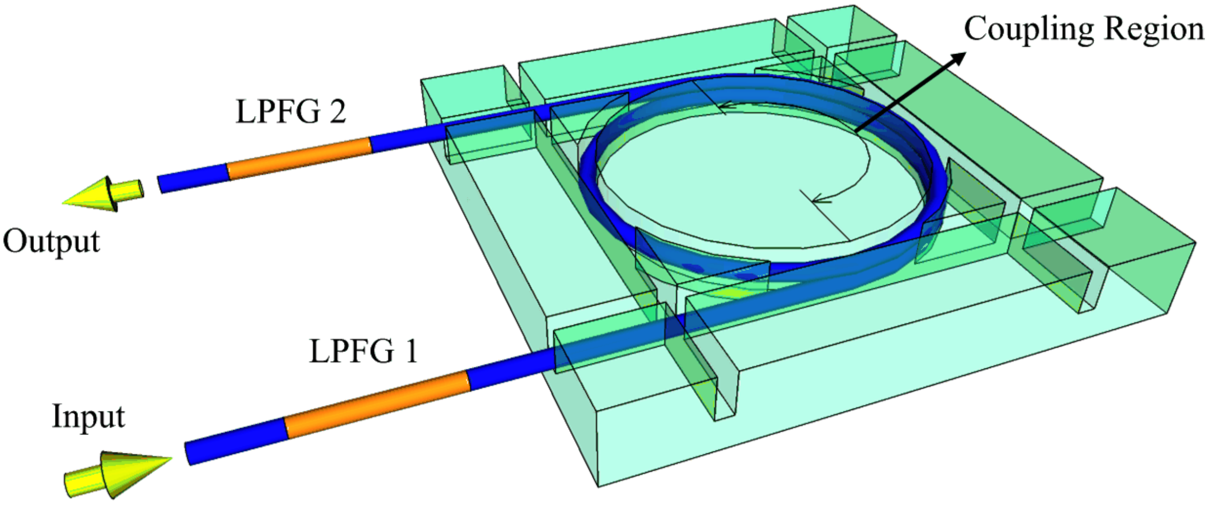

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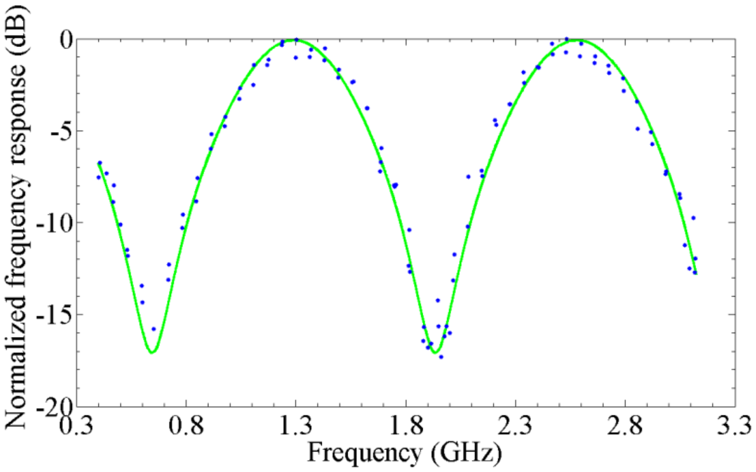

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