Novel Photonic Filter and Receiver based on Whipering Gallery Mode Microresonators

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Abstract:

We describe two new devices based on whispering gallery mode microresonators. The first device, a multipole filter, is based on coupled microresonators, the frequency of which is trimmed in situ to produce the desired filter function. The second device is based on a lithium niobate microresonator, which can detect applied microwave signals with power as low as 2.5 nW.

Introduction

Photonics technology offers the potential for improved efficiency and size in application of high frequency microwave communications and data processing. Many applications at Ka-band and Q-band have already been demonstrated, while systems at 60 and 90 GHz range are being investigated. Since ordinary electronic, microwave components such as amplifiers and high Q filters exhibit significantly lower efficiency, implementation of communications and data processing systems at these frequencies with conventional technology has proved cumbersome. By contrast, photonics components offer the opportunity for designing and implementing highly efficient systems based on new architectures.

A significant advance in the implementation of RF-photonic systems may be based on the whispering gallery mode (WGM) optical microresonators. In previous works we have demonstrated several functions based on these elements that draw their high Q from extremely low material, bending, and scattering losses associated with WGM modes at optical communications wavelengths. In this paper we discuss two new developments pertaining to high Q photonic filters, and a photonic receivers. In our previous work [1] we demonstrated a multipole filter with coupled microspherical resonators. This approach can provide filter functions with sharp skirts, as required in many applications, but is extremely sensitive to the coupling geometry. Thus its implementation in our previous work was tedious, and suitable only for laboratory demonstrations. As discussed below, we have developed and demonstrated a new scheme that allows trimming the mode of coupled microresonators *in situ* to achieve the desired filter shape. This approach is easy to implement, and is suitable for rapid processing and fabrication of the photonic filter.

The second study described here is based on the lithium niobate WGM microresonator, which we had used to demonstrate a 10 GHz modulator with less than1 W of applied RF power. An improved resonator presented below operates much more efficiently, with about 1 mW of RF power. Moreover, the device can be used as a photonic receiver capable of detecting signals as low as 2.5 nW. Such a sensitive receiver is particularly useful in systems at frequency higher than 10 GHz, where the receiver efficiency is low, and power consumption is high.

High Q Photonic Filter

A single microcavity produces a Lorentzian-shaped filter function. There is nevertheless a demonstrated approach based on coupling resonators in parallel or series to obtain a passband that is nearly flat [2], with significantly increased out of band signal rejection level. Series coupling can lead to a theoretically better performance [3].

We had previously given a preliminary report on the demonstration of such a configuration using two coupled microcavities. Since the filter function is sensitive to the details of the two-cavity coupling geometry, such a demonstration is tedious and time consuming and requires careful adjustment. We have extended this preliminary work by controlled tuning the resonance frequency of one of the cavities [4] very close to the resonance of the second cavity, and thus succeeded in producing a two-cavity compound filter with a nearly top hat second order filter function in a simple way.

To accomplish this tuning, we exploited the photosensitivity of germania-doped silica When exposed to UV light, this material undergoes a chemical change which alters its index of refraction. This is the same property that is used in writing fiber Bragg gratings. With microresonators, the change in the index of refraction results in a uniform translation of the resonant frequencies of a microcavity.

The experimental setup consits of a 1550nm laser diode which is current modulated with a sawtooth signal, so that the frequency varied non-linearly with time. To increase the laser power, the output from the diode passes through an EDFA. One half of this output goes to a Fabry-Perot cavity (FSR 20 GHz) which acts as both a reference to correct for laser frequency drift, and a scale to measure the spacing between resonance lines. The other half is sent through an angle-polished fiber, which serves as an input coupler to the first microcavity. The two cavities are placed near each other and adjusted to achieve a coupling. A second angle-polished fiber serves as an output coupler. The light from the output coupler is then routed to a photodiode, so that a plot of current vs. time is obtained as the frequency spectrum of the combined system. Finally, the UV fiber with a convex tip focuses the output of an argon-ion laser onto the surface of the first resonator.

The first resonator was fabricated from germania -doped silica, the core material from a germania-doped optical fiber. For the

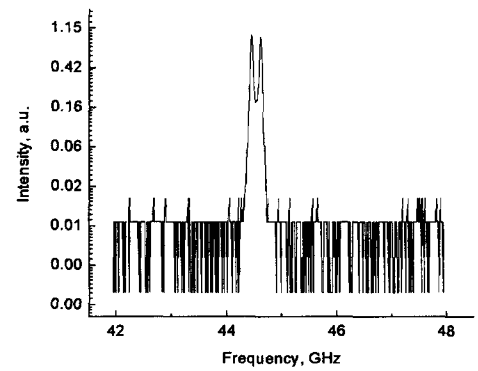
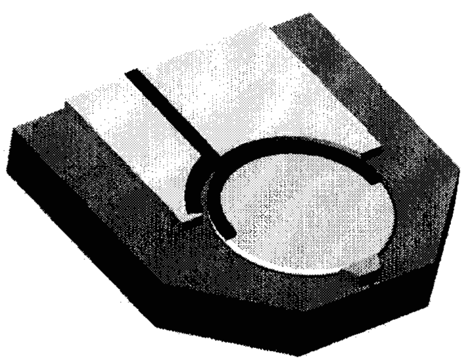


Fig.1. Optical spectrum of two coupled microresonators. The spectrum was obtained by irradiating the germanium doped resonator with UV light.

second microcavity, we used microspheres of pure silica, with approximately the same diameter as the first cavity. For these resonators, the mode structure of the second cavity remained unchanged throughout the experiment, despite exposure to small amounts of reflected and refracted UV light.

After proper alignment, the UV laser is tuned to 351 nm, which is the most photochemically efficient wavelength available from our argon laser. Fig.1 depicts the filter function obtained from an experiment involving a germania-doped microtorus and a pure-silica sphere. During irradiation one of the peaks is stationary, while the other peak moves towards it, and then passes through it. At the point where the two peaks overlap, a single-frequency compound filter whose bandpass is much sharper than that of either of the component linewidths is realized. On either side of this point, we also get notch-filters of varying depths.

Thus, we have demonstrated a new technique for resonance tuning of a microresonator, and produced a coupled system of two microcavities. This system exhibits a second order filter function with a sharp rolloff. We expect that the technique may be used to produce other complex filter functions with any desired line shapes.



Photonic Receiver

Fig. 2 Lithium niobate microresonator with diamond prism and the microwave coupling structure.

Photonic front-end microwave receiver architectures have emerged as a new approach for microwave and millimeter wave signal processing. The existing prototypes based on conventional electro-optic modulation techniques have reported sensitivity of 10 mW with analog bandwidth ~6 MHz [5]. Highly efficient front-end frequency up-conversion into the optical domain can be achieved by resonant interaction of light and microwaves in nonlinear--optic whispering-gallery (WG) resonator superimposed with a miniature microwave cavity. A new kind of electro-optic modulator and a microphotonic receiver based on this interaction have been recently suggested and preliminary experimental data were reported with microwave sensitivity at the level of 160 μW [6].

We demonstrate a microphotonic receiver with orders of magnitude improved sensitivity. The minimal detectable microwave power is 2.5~nW with about 14 dB signal-to-noise ratio, corresponding to the noise floor at approximately 0.1nW, and about 5 kHz analog bandwidth. This performance may be further enhanced by increasing the quality factors, and by improving the overlap between microwave and optical fields. Used as an electro-optical modulator, the microwave receiver demonstrates high efficiency light modulation with small drive microwave power (~ 1mW operational power and ~ 10mW full saturation).

In our experiment 2 mW of1550 nm light from a distributed feedback (DFB) laser is launched into a Z-cut $LiNbO_3$ optical cavity via a diamond prism (Figure 2). The laser is then tuned to the vicinity of a particular cavity mode. The cavity is a thin disk with radius of 2.4 mm, thickness of 150 μm, and with perimeter edge polished into a toroidal geometry with transverse curvature diameter of 180 μm. The C-axis of the $LiNbO_3$ crystal coincides with the symmetry axis of the cavity within 0.1 degree uncertainty. The loaded optical quality factor of WG modes is 5×10^6 (optical resonance bandwidth of 30 MHz). The field confinement area of the optical WG modes overlaps with that of a microwave resonator that is excited by a microstripline coupler delivering the input microwave signal. The quality factor of such a microwave cavity is 120 with a bandwidth of about 80 MHz. We studied the dependence of light modulation as a function of frequency of the input microwave signal power. The typical frequency response of the device is shown in Fig.3. Here the laser is constantly kept at the slope of the resonance curve of an optical modes, while the microwave frequency is applied, and the demodulated microwave power produced by a photodetector is recorded by a network analyzer.

The curves in Fig. 4 are well under the saturation limit shown by zero dB level. The resonances.

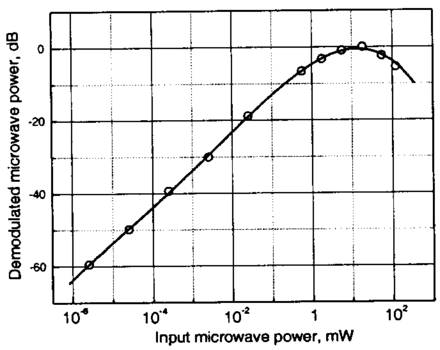


Fig. 3 Frequency response of the microwave modulation. Zero dB level corresponds to saturation.

smallest detected microwave power was about 2.5 nW with 14 dB signal-to-noise ratio. The noise floor, i.e. sensitivity of our photonic receiver, is therefore at the level of 0.1 nW, with microwave detection bandwidth of the network analyzer at 5 KHz. To compare our results with previously reported data on conventional modulator-based photonic receiver [5]. We note that the detection noise floor in terms of detectable microwave power increases proportionally to the measurement bandwidth. It would therefore be at the level of 0.1 μW with the bandwidth of 5 MHz similar to that of \cite{ohata96ieee}. Thus we have improved previously reported sensitivity by two orders of magnitude.

Amplitude characteristic of our modulator/receiver was observed as the dependence of the demodulated microwave power, obtained by a high-speed photodetector at the optical output of the modulator, on the input microwave power. Results are presented in Figure 4. Saturation point at about 10 mW corresponds to the limit imposed by harmonic multiplication as well as the power broadening. This shows that our photonic receiver can be used as an effective electrooptic modulator. Optimal operational power within linear regime of the modulator is about 1 mW, and the dynamic range of the receiver is 70 dB.

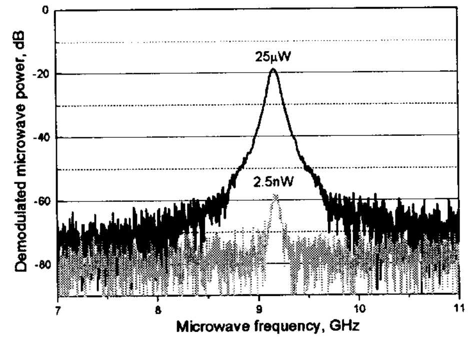


Fig. 4 Microwave response of the device.

The system may produce both phase and amplitude modulation signals. When the pump laser is tuned to the slope of the optical resonance, the modulation is mostly of the amplitude-type. The modulation is of phase-type for the resonant laser tuning. The dependence of the demodulated microwave power on the pump laser frequency detuning from the optical resonance is shown in Figure 4. Amplitude modulation is a maximum when the laser is tuned to the slope of the resonance curve of WG mode curve, and equals to zero exactly at optical resonance.

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