Experimental Demonstration of Dynamic Bandwidth Allocation Using a MEMS-Actuated Bandwidth-Tunable Microdisk Resonator Filter

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***Abstract*—A novel bandwidth-tunable optical filter based on a microelectromechanical-system-actuated microdisk resonator is utilized for dynamic bandwidth allocation. The filter bandwidth can be dynamically adjusted by voltage tuning the gap spacing between the two waveguides and microdisk. Three key applications of dynamic bandwidth allocation are demonstrated experimentally. Matched optical filtering is achieved on 5-Gb/s nonreturn-to-zero (NRZ) signals with error-free (10^{-9} bit-error-rate) data transmission. Reconfigurable channel banding of three 2.5-Gb/s NRZ signals is demonstrated by either routing a single or a group of data channels. Wavelength demultiplexing of three channels under the worst-case scenario shows 14.5-dB suppression with error-free operation.**

***Index Terms*—Bandwidth-tunable filter, channel banding, dynamic bandwidth allocation, microresonator, optical microelectromechanical system (MEMS).**

I. INTRODUCTION

WAVELENGTH-SELECTIVE devices are crucial building blocks for many types of wavelength-division-multiplexed (WDM) optical communication systems. Since wavelength determines the routing in a typical WDM network, the ability to manipulate the spectral characteristics of in-line devices can be quite advantageous. These components are commonly optical filters, wavelength (de)multiplexers, and add–drop modules. The often-reported optical spectral manipulation is to tune the center wavelength of a device, such that a given wavelength data channel will either be added, dropped, or passed.

However, tuning the spectral width of the device passband has been quite a challenge for device researchers. The highly laudable systems application of a bandwidth tunable filter would include any type of *dynamic bandwidth allocation* for optimal spectral efficiency, as conceptually shown in Fig. 1.

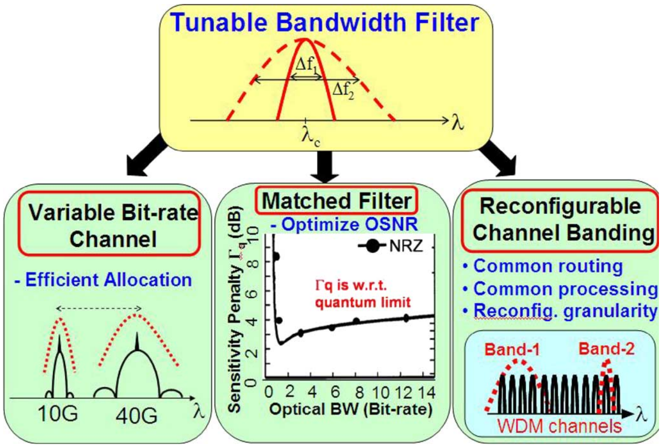

Fig. 1. Conceptual diagram of system-level applications of a tunable bandwidth optical filter for dynamic bandwidth allocation: 1) efficient allocation for variable bit-rate systems; 2) optimization of OSNR using matched optical filtering for a specific data-rate; 3) reconfigurable channel banding for common routing, signal processing of data channels.

1) *Variable bit-rate channels*: Coexistence of hybrid bit-rates and data formats is highly likely in heterogeneous optical systems. A bandwidth-tunable filter will enable efficient allocation according to incoming data rates and formats [1]. 2) *Matched optical filtering*: For a static system that runs at a specific bit rate, one would like the ability to optimally filter this single channel to minimize the power penalty without wasting excess bandwidth [2]. 3) *Reconfigurable channel banding*: The ability to dynamically route either a single data channel or a contiguous set of data channels to a specific destination will enable advanced network routing and signal processing functionalities [3]. Reconfiguration granularity determines the highest banding resolution and is thus essential for efficient channel banding.

To date, there have been a few published reports of devices that are tunable in the bandwidth and center wavelength [4]–[7]. These reports showed the spectral static-tuning characteristics. However, to the best of our knowledge, there has been no report of system performance evaluation for actual data traffic being transmitted through the unique devices under different bandwidth and wavelength conditions.

In this letter, we experimentally demonstrate dynamic bandwidth allocation of matched optical filtering, tunable channel banding, and wavelength demultiplexing using a novel add–drop optical filter based on a microelectromechanical-system (MEMS)-actuated microdisk resonator. The filter

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Manuscript received May 21, 2007; revised June 28, 2007.

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Digital Object Identifier 10.1109/LPT.2007.903872

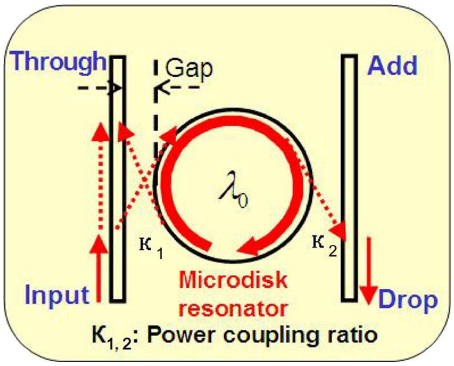

Fig. 2. Principle of the MEMS-actuated microdisk resonator filter. The bandwidth of the filter can be tuned by controlling the gap spacing, which results in changing the power coupling ratio.

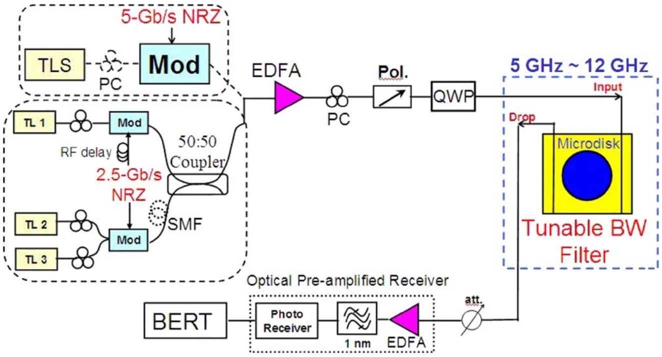

Fig. 3. Experimental setup of both single and WDM channel systems for demonstration of dynamic bandwidth allocation functionalities. EDFA: erbium-doped fiber amplifier. QWP: quarter-wave plate.

bandwidth can be dynamically adjusted by voltage tuning the gap spacing between the microdisk and the two waveguides. Error-free [10^{-9} bit-error-rate (BER)] data transmission for matched optical filtering of a 5-Gb/s nonreturn-to-zero (NRZ) data channel is demonstrated. Reconfigurable channel banding of three 2.5-Gb/s NRZ data channels is achieved by either routing a single or a group of data channels. Demultiplexing of three WDM channels under the worst-case scenario shows more than 14.5-dB suppression ratio with error-free operation.

II. THEORY OF BANDWIDTH-TUNABLE FILTER

The bandwidth-tunable filter consists of a high-Q microdisk resonator ($R = 20$ μm), an input and an output deformable waveguide whose cross section is 0.8 μm by 0.25 μm. The waveguide is suspended around the microdisk and the gap spacing is defined as the distance from the waveguide to the edge of the microdisk, as shown in Fig. 2. Upon MEMS actuation, the waveguide is deformed and attracted towards the microdisk. The gap spacing is thus reduced and the power coupling ratio κ_1 and κ_2 is changed accordingly. Therefore, the device operation from under- to over-coupling is achieved. Correspondingly, the resonant wavelength is switched from the through port to the drop port. Device details on the sample layout can be found in [8].

According to the time-domain coupling theory [9], the amplitude transfer function of the drop port is expressed as

$$T_{\text{drop}}(\omega) = \frac{\sqrt{\kappa_1 \kappa_2}/T}{j(\omega - \omega_0) + (\gamma - \kappa_2 - \kappa_1)/2T}$$

where ω_0 is the resonant frequency, T is the round-trip time, and γ is the round-trip loss. By biasing with different voltages, the MEMS actuators can independently control the two gap spacing, and thus the coupling ratio κ_1 and κ_2, between the waveguides and microdisk. In general, as both κ_1 and κ_2 are much larger than the resonator loss γ, the filter bandwidth and extinction ratio increase with coupling ratio if κ_1 matches κ_2, which is known as wideband operation. On the other hand, for narrowband operation, to achieve maximum extinction in the through port, $\kappa 1$ (input) should be equal to the sum of $\kappa 2$ (output) and γ. This can be verified by the time-domain coupling theory. Based on the equation, the lower limit of the bandwidth is bounded by the intrinsic microresonator loss whereas the maximum achievable bandwidth is limited by the phase matching between the microdisk and the waveguide. The filter center wavelength can be changed independently by temperature-tuning (0.1 nm/°C).

III. EXPERIMENTAL RESULTS

The experimental setup of both the single– and WDM-channel systems is shown in Fig. 3. For the single-channel case, one tunable laser source (TLS) is externally modulated by 5-Gb/s NRZ $2^{23} - 1$ pseudorandom binary sequence (PRBS) data signals. For the WDM case, three TLSs are modulated by 2.5-Gb/s $2^{23} - 1$ PRBS NRZ signals. RF delay lines and single-mode fibers (SMFs) are used for decorrelation among channels. The input signals are controlled to be transverse-electric (TE) polarized by a polarization controller and a polarizer followed by a quarter-wave plate. Spherical lensed fibers with spot size of 2.5 μm are used as the input and output fibers. For this specific experiment, the sample dependent microresonator filter has a tunable bandwidth range from 5 to 12 GHz. Wider tuning ranges from 12 to 41 GHz [6] and from 2.8 to 78.4 GHz [7] can be utilized for higher bit-rate operation. The preamplified receiver is used for BER characterization.

Matched optical filtering is demonstrated on a single 5-Gb/s NRZ data signal. By bandwidth tuning the MEMS-actuated microdisk resonator filter, we investigate the system power penalty at 10^{-9} BER as a function of the tunable passband (Fig. 4). The optimum bandwidth (corresponds to minimized power penalty) is found to be 10 GHz. A smaller bandwidth cuts down higher frequency components and leads to intersymbol interference due to pulse broadening. For wider bandwidth, the small penalty comes from the additional amplified spontaneous emission noise. Furthermore, the nonlinear phase response determines the dispersive properties of these filters [8], and might distort the signal and lead to system degradation [10]. This limitation will likely prevent the filter from being an optimal matched filter.

Reconfigurable channel banding is demonstrated on a WDM system and consists of three 2.5-Gb/s NRZ data signals at a fixed channel spacing of 7.5 GHz, as shown in the experimental setup of Fig. 3. The bandwidth-tunable filter is adjusted to either reroute a single channel ("Band 1") or a group of data channels ("Band 2"), with the bandwidth tuned to be either 6.5 or

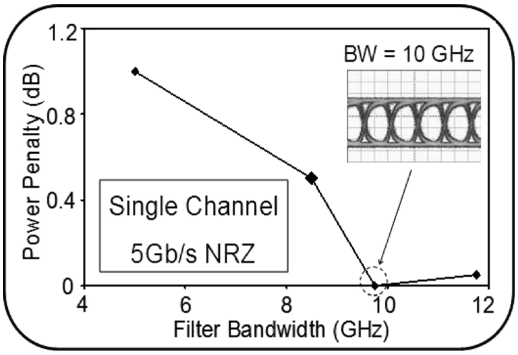

Fig. 4. Matched optical filtering: One 5-Gb/s NRZ data signal is passed through the MEMS-actuated microdisk resonator filter. The filter bandwidth is tuned so that the system power penalty is minimized.

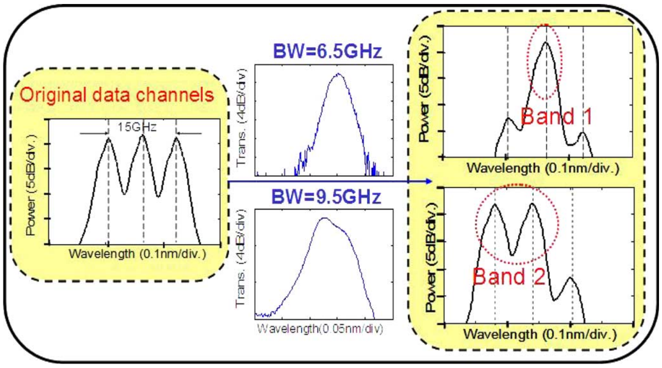

Fig. 5. Reconfigurable channel banding: The filter is adjusted to either route a single data channel (when bandwidth is 6.5 GHz) or a group of two data channels (when bandwidth is opened up to 9.5 GHz).

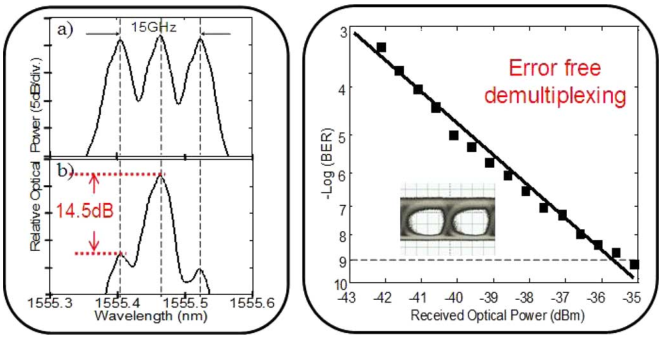

Fig. 6. Error-free wavelength demultiplexing: Spectrum on the left shows 14.5-dB suppression ratio under the worst-case scenario. BER measurement shows error-free demultiplexing.

9.5 GHz, respectively (Fig. 5). When only one channel is selected ("Band 1"), the extinction ratio is measured to be 14.5 dB with respect to the adjacent channels. When two channels out of three are selected and routed ("Band 2"), the filter bandwidth needs to be opened up to 9.5 GHz and the center wavelength is tuned to the middle of the two channels. The extinction ratio shown in the spectrum of Fig. 5 is 13.9 dB. Note that wider bandwidth tuning ranges [6], [7] will allow higher speed operation and accommodate more flexible channel banding situations.

Demultiplexing of three 2.5-Gb/s WDM channels is demonstrated under the same condition as in the above channel banding experiment. Fig. 6(a) and (b) shows the spectrum of the three channels before and after demultiplexing. By adjusting the filter bandwidth to be 6.5 GHz and temperature-tuning the center wavelength, we are able to effectively select and detect the middle channel, which corresponds to the worst-case scenario due to the most channel crosstalk from its neighborhood. The suppression ratio between the middle and the adjacent channels is 14.5 dB. Error-free demultiplexing is achieved and shown in Fig. 6, even for this worst-case scenario.

IV. CONCLUSION

Dynamic bandwidth allocation was experimentally demonstrated using a novel bandwidth-tunable optical filter based on a MEMS-actuated microresonator. The bandwidth was adjusted by voltage tuning the gap spacing between the microdisk and the waveguides. Three key system functionalities of using dynamic bandwidth allocation were demonstrated. Matched optical filtering was achieved on a 5-Gb/s NRZ channel with error-free transmission. Reconfigurable channel banding of three 2.5-Gb/s NRZ signals was also shown by either routing a single or a group of data channels. Wavelength demultiplexing of three WDM channels under the worst-case scenario shows more than 14.5-dB suppression with error-free operation. The demonstrated functionalities address the importance and usefulness of a bandwidth-tunable filter in a dynamic bandwidth allocation environment for optimal spectral efficiency and reconfigurable channel banding.

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