high-frequency operation can be realized by reducing ΔL_{eff}. Figure 4(b) shows an FSR tunable from 0.719 GHz to 1.57 GHz. The FSR can be increased by reducing ΔL_{eff} until being limited by the optical modulation bandwidth of the laser, which is typically on the order of 10 GHz. Tuning of the negative-tap filter is summarized in Fig. 5, where the measured data in circles are fit to the curve for group index $n_g = 1.45$. Fine-tuning of the FSR is allowed by precisely adjusting the translators. From Eq. (1), even with a modest mechanical precision of 0.2 mm in our setup, the precision of FSR is better than 0.1% when operated at FSR = 1 GHz. The tuning range of ΔL_{eff} is limited by the lengths of the bare fibers that can be maneuvered, which is typically up to a few tens of centimeters. Such precise and wide tunability offered by the cladding-mode coupler is difficult to achieve with conventional delay-tuning approaches.

It is possible to extend the current configuration to accommodate more taps. A simple approach to realizing two negative taps is to tap out some light from the first delay path with a fiber coupler (at a position before LPFG1 in Fig. 1), transmit the tapped signal through a second delay path that consists of another set of LPFG pair and cladding-mode coupler, and combine the output signal from the second delay path with the signals from the original paths. To avoid PIIN, a polarization controller should be inserted in the second path to ensure orthogonal polarization states between the two negative taps. A variable optical attenuator can also be inserted in the second delay path to control the magnitude of the tap coefficient. A general approach to realizing N negative taps is to employ N slave lasers of different free-running wavelengths locked by the same master laser. The inverted signals at the N wavelengths are extracted, respectively, by N stages of LPFG pair and cladding-mode coupler, which are connected in series through the idle output ports of the cladding-mode couplers. The LPFG pair at each stage is designed to operate only at the assigned signal wavelength. The output signals from the N stages and the non-inverted signal from the master laser are finally combined to produce the filter output. The tap coefficients can be varied independently by adjusting the polarization controllers that control the injection locking of the slave lasers. The maximum number of negative taps that can be achieved is mainly limited by the bandwidths of the LPFGs and the number of slave lasers that can be locked effectively with a single master laser.

4. Conclusion

In summary, a tunable negative-tap photonic microwave filter is proposed, which employs a largely detuned injection-locked laser for signal inversion and a cladding-mode coupler for compact, precise, and continuous tuning. The use of a pair of LPFGs in conjunction with the cladding-mode coupler enables both optical filtering and delay tuning. An experimental filter was demonstrated with an FSR tunable from 88.6 MHz to 1.57 GHz with a notch depth larger than 35 dB. Optical injection locking with wavelength detuning as large as 27 nm was achieved. The approach is readily extended to multiple-tap filters, as multiple path lengths can be adjusted precisely using cladding-mode couplers.

Acknowledgments

The work described in this paper was fully supported by two grants from City University of Hong Kong [Project Nos. CityU 7002444 and CityU 7002448].

#142619 - $15.00 USD Received 15 Feb 2011; revised 24 May 2011; accepted 27 May 2011; published 7 Jun 2011