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**Abstract:** We experimentally validate silicon photonics for passive optical networks enabling radio over fiber on wavelength slots. We detect an 8 GHz OFDM signal and five 125 MHz RF signals, and remodulate RoF onto a clean carrier.

**OCIS codes:** (060.2330) Fibercommunications; (130.0130) Integrated optics; (060.1155) All-optical networks.

## 1. Introduction

Passive optical networks (PONs) can accommodate heterogeneous radio-over-fiber (RoF) signalling for 5G femtocells [1, 2] as well as basic broadband access with wavelength division multiplexing. These solutions must be compatible with colorless operation over a single feeder infrastructure as carrier reuse is reduces PON system complexity. Carrier reuse limits the carrier power available for direct detection, particularly against signal-to-signal beating interference (SSBI). Detection schemes such as Kramer-Kronig avoid SSBI, however, the carrier must typically be 6 dB stronger than the signal [3]. We assume the simple expedient of a large guard band to avoid SSBI and conserve carrier power. We propose the addition of RoF 5G services to recuperate the guard band; service provides achieve a secondary revenue stream while boosting effective spectral efficiency.

We demonstrate a silicon photonic (SiP) subsystem for the optical line terminal (OLT) use to receive PON transmission of RoF signals in the guard band of an orthogonal frequency division multiplexing (OFDM) broadband signal. Our SiP filtering solution assures the OFDM and RoF signals are isolated at detection to avoid signal-to-signal beating. OFDM is favoured in PONs because of its flexibility in both frequency and time domain multiplexing, particularly the single side band variant [4]. We present the simultaneously detection of RoF and OFDM signal via on-chip photodetectors. At the same time, better suppression on OFDM and RoF signal compared to carrier provides the convenience for carrier reuse for uplink signal modulation. We use an on-chip SiP microring modulator to send an uplink RoF signal on the remodulated carrier.

## 2. Subsystem Design

The subsystem architecture and principle of operation is illustrated in Fig. 1 insets. The OFDM signal has a guard band as wide as the data bandwidth. Narrowband RoF signals in the guard band increase spectral efficiency. We use separate two-bus microring resonators (MRRs) to isolate the disparate signals (OFDM and RF), each time leeching off enough carrier power for good detection. MRRs outperform other filtering methods due to their ultra low cost and small size. By cascading two MRRs we achieve the function of notch filter with adjustable roll-off and extinction ratio. We cascade two MRRs via the drop port; metal deposits allow us to tune the two rings individually. An on-chip microring modulator (MRM) generates the RoF uplink in our demonstration.

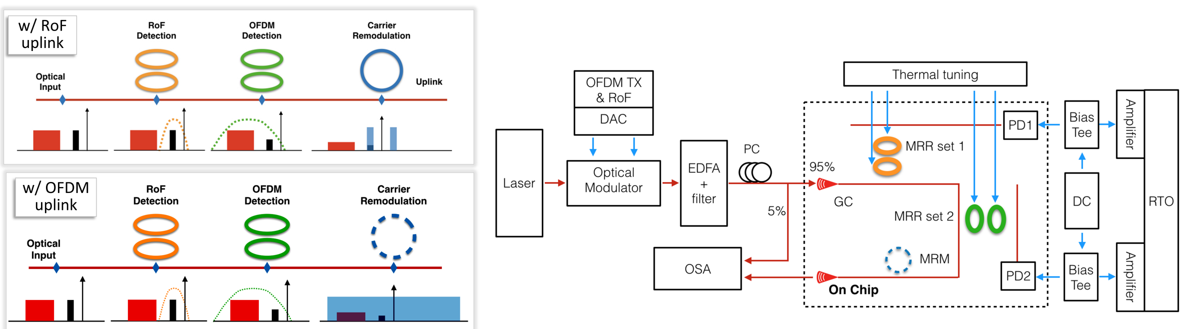


Fig. 1: Principle of operation and experimental setup.

Since the RoF is narrowband and closest to the carrier, we will use a single resonance peak in the first set of MRRs to drop the entire RoF signal and a small percentage of carrier power to an on-chip photodetector. The OFDM signal and most carrier power exits the through port of the first MRRs and is routed to the second set of MRRs. There we drop the OFDM signal and again a part of the carrier to the photodetector. Finally, the residual carrier is reserved for remodulation using an on-chip microring modulator (MRM).

The RoF and the wideband OFDM signal are detected separately. The large guard band avoids SSBI for OFDM detection. The RoF detection will suffer only a very limited portion of the OFDM signal dropped by the cascaded rings. We focus on the RoF uplink for this demonstration using a narrowband MRM. OFDM uplink could be solved various ways, with a standard (illustrated) or an IQ modulator.

## 3. Experimental Setup

The experimental setup is illustrated in Fig. 2. The tunable optical source is a Cobrite external cavity laser with 100 kHz linewidth. We generate the RoF and OFDM signals (both QPSK) offline with Matlab. The FFT size is 1024, covering 64 GHz (DAC sampling rate of 64 GS/s). Five 125 MHz RoF signals are generated over 2 GHz with 250 MHz spacing between channels. The wideband OFDM signal includes 127 subcarriers, occupying just below 8 GHz, with an 8 GHz guard band. Single sideband (SSB) OFDM has complex coordinates, using two 8-bit DAC channels. An Inphi amplifier amplifies the DAC output which is sent to an SHF IQ modulator to generate the SSB signal. The bias point is shifted from the null point to generate stronger post-modulation carrier.

Due to limited DAC dynamic range and bandwidth we use clipping (5 dB peak-to-average threshold) and pre-compensation (equalizing OFDM subcarrier performance). Polarization control was used as this silicon photonics subsystem did not include polarization diversity subsystems. Most power of the optical signal is coupled into the chip via a 250 $\mu$m spaced fiber array, while a small part (5%) is routed to an optical spectrum oscilloscope (OSA). The round trip coupling loss is 13 dB. To compensate that loss, the signal is amplified by an EDFA and then filtered by a 0.7 nm bandpass filter before coupling.

The integrated components are contained in the dotted rectangle. Each set of MRRs drop a desired signal (RoF or OFDM) to a photodiode. The four rings are thermally controlled with separate DC inputs. The photodetectors are both reverse-biased with 4 V voltage via bias-tees. The output of the on-chip photodetectors are amplified and then captured by real-time-oscilloscope (RTO) with maximum 80 GS/s sampling rate and 32 GHz RF front end. The optical output is also connected to the OSA to observe the carrier power and downlink signal power changes.

## 4. Experimental result and discussion

Fig. 2a shows the cascaded MRR through port response (red solid curve) and the responses with different thermal tunings using one of the heaters (dotted curve). By applying different voltages on the heater, we could control the red shift of the response to move the response peak to the desired frequency. The more important feature is that by heating the two rings separately, we could change the response from sharp notches (extinction ratio more than 25 dB) to a shallow shape. Taking advantage of that, we could select the component of the downlink signal for photodetection. The two resonance peaks are spaced with more than 50 GHz, which is large enough to ensure the signal is filtered by only one notch.

### *4.1. Hybrid OFDM and RoF detection*

Figure 2b shows the optical spectrum at three different measurement points. The signal at the input to the chip is given in black. We see the carrier at 1.934e5 GHz, the five separate RoF signals to the left, and finally the 8 GHz wide SSB-OFDM signal. With two sets of cascaded MRRs and on-chip PDs, RoF and OFDM signals are detected.

The dotted orange curve in Fig. 2b above the five RoF signals is the approximate drop port frequency response of the first pair of MRRs. They are tuned to achieve critical coupling, thus creating a very narrow and deep notch. We drop a small portion of carrier and the entire RoF signal to the PD. The narrowband RoF signals was detected, with little residual undesired OFDM signal. Leaked OFDM power would have resulted in SSBI for RoF signal detection, as well as, degrading OFDM detection in the next stage of the receiver.

The red curve in Fig. 2b shows the spectrum after the RoF signal is dropped, i.e., the signal entering the second set of cascaded MRMs. We observe about 20 dB suppression of the RoF signals. There is little degradation of the OFDM signal, only a few subcarriers of the OFDM signal are influenced. The carrier power is reduced by 4 dB.

We set the RTO built-in low pass filter to 8 GHz and capture the detected signal at 20 GS/s. In the electrical spectrum only a small part of OFDM is dropped, resulting in interference at baseband (lower than 1 GHz). The five RoF signals at 2 GHz are unaffected by this interference which can be easily filtered out. The captured signal are down-sampled to 8 GS/s and digitally filtered to separate the five RoF channels. Only a small FFT size (128) is needed. For all five channels the BER is well under the forward error correction (FEC) threshold. The calculated Q-factor of the five RoF channels are 9.57 dB, 10.51 dB, 11.71 dB, 10.88 dB, 11.85 dB from low to high frequency.

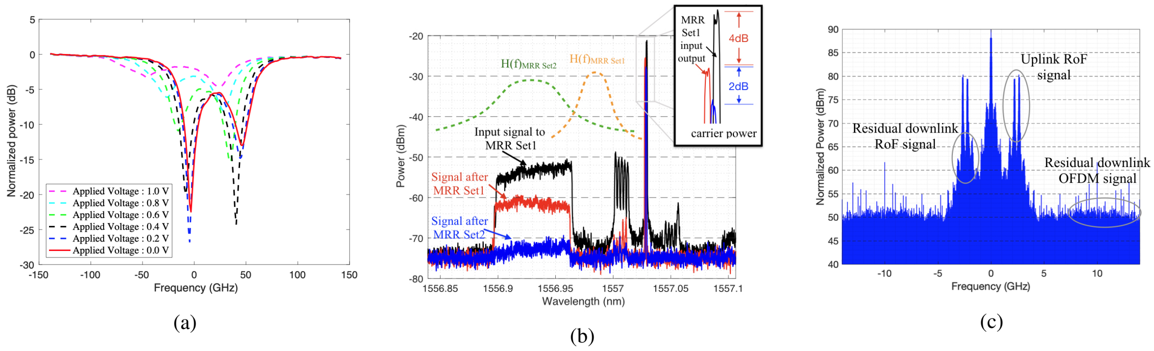


Fig. 2: a) MRR responses w/ thermal tuning, b) optical spectrum at three measurement points: black curve is input to chip, red curve is output of first pair of cascaded MRRs, blue curve is output of second pair of cascaded MRRs (frequency responses of each set of cascaded MRRs are sketched in dotted lines), and c) electrical spectrum of remodulated RoF uplink signal.

The strategy for OFDM detection is straightforward. As illustrated by the green dotted line in Fig. 2b, we tune the second set of MRRs to a shallow shape to allow a wide, flat passband for OFDM. The OFDM signal is captured by the RTO at 80 GS/s and 32 GHz electrical bandwidth. The normal FFT size (1024) is used. The BER is $3.205\times10^{-3}$, which is still below the 7% threshold.

The blue curve in Fig. 2b shows the spectrum after OFDM detection. The downlink OFDM signal is well suppressed while the carrier power is only decreased by 2 dB. Compared to KK scheme, we do not require 6 dB or more of carrier-to-signal-power ratio to avoid SSBI. While we use a large guard band, the spectral efficiency is compensated by transmitting RoF signals in this band. The RoF signals are almost buried by the noise after the second filtering. The whole OFDM signal receives more than 18 dB overall suppression.

### *4.2. RoF remodulation*

The residual carrier was routed to an on-chip p-i-n structured MRM with 20 $\mu$m diameter, and a gap between the ring and waveguide of 300 nm. This modulator has narrow bandwidth and was fabricated for use with RoF signals. The modulated uplink signal is coupled out of chip via the fiber array. The light is amplified by an EDFA and passes through a 0.7 nm optical filter before photodetection. The directly detected electrical signal is captured by the RTO. We count errors and infer the Q-factor from the measured BER.

The resonance peak of the MRM is tuned to the carrier location. Figure 2c shows the optical spectrum of the remodulated uplink signal and residual downlink signals. The downlink OFDM signal and the RoF signals both receive significant suppression. Two uplink RoF signals can be distinguished from the residual downlink RoF signals. With a suppression of 13 dB over the downlink, the two RoF uplink signals achieved Q-factors of 13.77 dB and 14.12 dB. This demonstration confirms hybrid detection is compatible with providing good carrier reuse for the uplink.

## 5. Conclusion

We have proposed a novel silicon photonics subsystem supporting detection of RoF signals as well as OFDM. The proposed subsystem improves the spectral efficiency and recovers the carrier to enable remodulation of uplink data within a single feeder PON architecture. The subsystem is fabricated and experimentally validated.


## 6. Acknowledgements

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