# Using Optical Ring Resonators for True-Time Delay: Investigating the Required Delay Bandwidth

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*Abstract — Integrated microwave photonics is an emerging technology of which optical true-time delay networks are an ongoing research topic. Optical true-time delay is directly transferred to true-time delay in the microwave domain after optical heterodyning. This time delay is used to control the steering direction of a phased array antenna in wireless communication systems. Optical ring resonators are often considered for the creation of optical true-time delay networks. However, the literature is inconsistent about the required delay bandwidth. In this paper, it is concluded that the entire optical signal (both tones and modulation) needs to experience a flat group delay response in order to get the proper delay in the microwave domain. This implies that the required delay bandwidth is larger than what is often assumed. Simulations are presented that support this statement.*

*Index Terms — Beam steering, microwave photonics, optical heterodyning, optical ring resonators, time delay.*

## Introduction

Global mobile network data traffic has been growing exponentially for the last decade. To sustain this growth, supporting technologies are in constant development. To increase the data rate, a higher signal bandwidth is needed, which often leads to moving to higher frequencies. To achieve an overall high antenna gain phased array antennas are often used. The steering direction of the phased array needs to be controlled by true-time delay (TDD) to avoid beam squint [1], [2]. This time delay can also be applied in the optical domain. The applied delay will transfer directly to the microwave domain after optical heterodyning. To create an optical true-time delay (OTTD) network optical ring resonators (ORRs) can be used. However, the literature is inconsistent about the required delay bandwidth. This paper shows that the delay bandwidth must be wide enough to fit the complete single sideband (SSB) optical signal. Simulations are presented to support this statement. The work presented here is part of the graduation work available at [3].

## Optical Ring Resonators for Optical True-Time Delay

An introduction to ORRs is out of the scope of this paper, the reader is referred to for example [4], [5]. The group delay response of an ORR, which is defined as the negative derivative of the phase transfer function with respect to angular frequency, is a bell-shaped delay profile with the same free spectral range (FSR) as the power transfer function of the ORR. The phase and group delay response are visualized in Fig. 1. The maximum group delay occurs at resonance and the minimum group delay occurs at anti-resonance. Note that the induced phase shift stays the same at these points.

ORRs can be used to create OTTD since the group delay experienced by the optical signal will translate to TTD in the microwave domain after optical heterodyning. The delay bandwidth is defined as the bandwidth over which the group delay response stays relatively constant. There is an inherent trade-off between delay bandwidth and maximum delay because the area underneath the bell-shaped group delay response over one FSR is fixed. It is important to realize that the entire optical signal (both tones and modulation) needs to fit in this delay bandwidth to use it as OTTD.

In the literature, some inconsistencies were found around the statement made above.

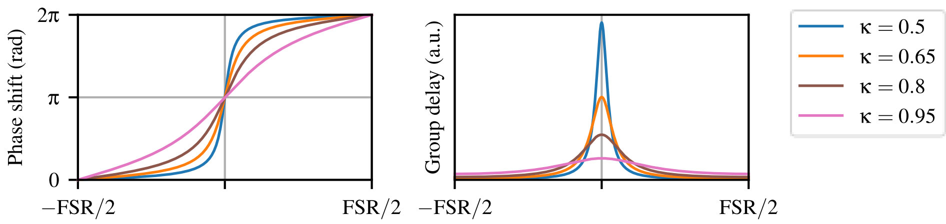


Fig. 1. Phase and group delay response of a single ORR over one FSR for different values of coupling κ (cross-coupling to the ring) [4]. The ORR is assumed to be lossless.

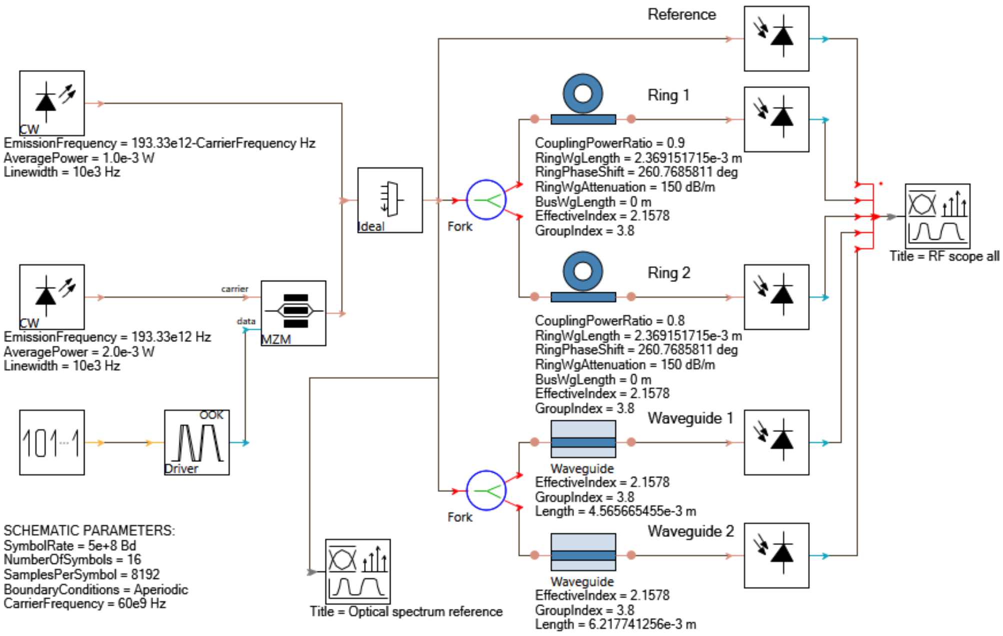


Fig. 2. Schematic of the simulation performed in VPIcomponentMaker Photonic Circuits [20].

Some works using ORRs for OTTD applications give the impression that the delay bandwidth of the ORR(s) only needs to be wide enough to fit the bandwidth of the modulation and not the complete SSB optical signal. They do not mention or implement a solution to get the phase relation between the two optical tones correct. Part of them only show simulations and part of them show experimental demonstrations which are not set up in such a way that the working of OTTD at a carrier frequency higher than the given delay bandwidth, is proven. To the best of the author's knowledge these works include [6], [7], [1, Chapter 5.2], [8], [9], [10], [11], [12], [13], [14], and [15]. One work was found that also explains the described problem [16, e.g. Fig. 4]. Another work [17] acknowledges the problem and implements separate carrier tuning (SCT) [18] to get the phase relation between the two optical tones correct. A different work [19] acknowledges the statement made and implements some novel ideas to increase the delay bandwidth.

## Supporting Simulations

To support this statement, a simulation is performed as shown in Fig. 2. The simulation is based on the design presented in [6], most of the parameters are made very similar. An SSB signal is generated by two lasers, of which one is modulated by a 0.5 Gb/s NRZ signal. The spectrum is shown in Fig. 3. This signal is sent through two different ORRs and two different lengths of straight waveguide, see Fig. 4 for the transfer characteristics.

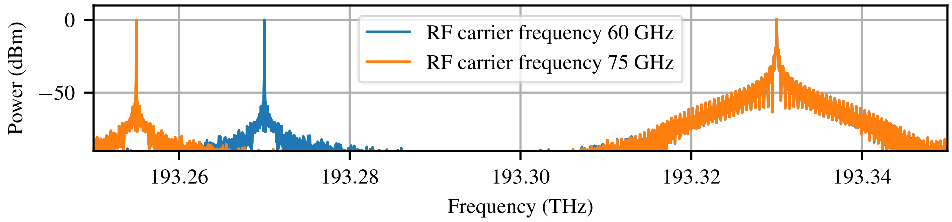


Fig. 3. Optical spectra for the two simulations that will result in a different RF signal. For both, data is modulated on the right tone, which is fixed at 193.33 THz, hence they overlap.

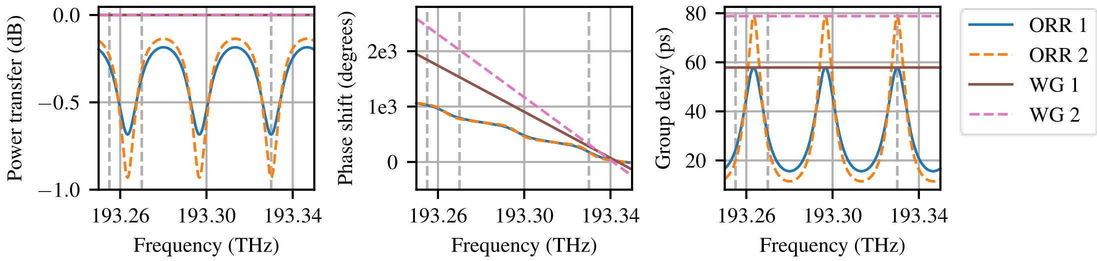


Fig. 4. Transfer characteristics of the two ORRs and the two sections of straight waveguide (WG). The two ORRs only differ by coupling coefficient. The length of the two waveguides is chosen such that the group delay is the same as the peak value of the group delay from the two ORRs. The vertical dashed gray lines indicate the location of the laser tones as shown in Fig. 3.

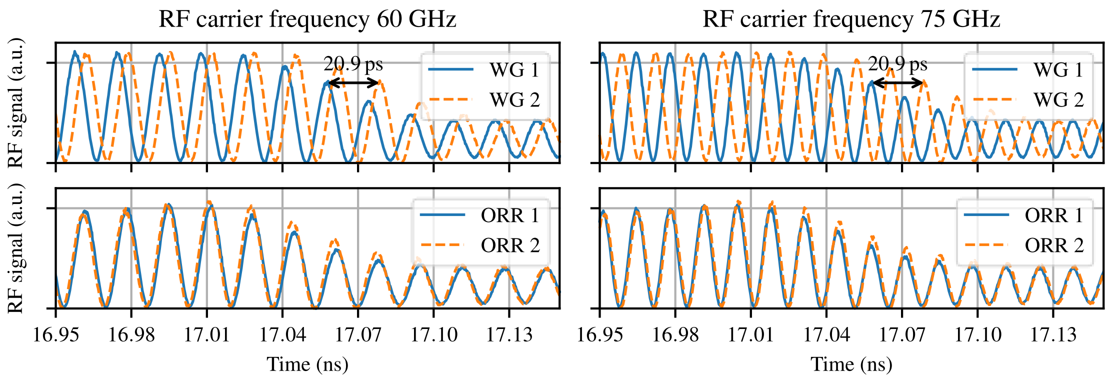


Fig. 5. Time domain results after optical heterodyning for a carrier frequency of 60 GHz and 75 GHz.

Optical heterodyning is performed using separate photodetectors (see Fig. 2). The resulting radio frequency (RF) signals are measured in the time domain, presented in Fig. 5. The sinusoidal signals that can be seen are the RF carrier frequencies. Only a small time frame around one transition period is shown: when the data modulation goes from a 1 (high) to a 0 (low). This makes it easier to see the time delay between the different signals and to know which periods of the sinusoidal signal to compare.

From Fig. 5 it can be concluded that, for both carrier frequencies, the signals going through the two different waveguides experience a relative delay difference of 20.9 ps, which is equal to the difference in group delay as shown in Fig. 4. However, there is no relative delay difference present between the signals that passed through the two different ORRs. Two different RF carrier frequencies were used to strengthen the conclusion that:

- The shift between the two signals, due to a different length of waveguide, is actual OTTD and not a phase shift in the carrier frequency.
- The two signals that passed through the different ORRs lay on top of each other and the time delay is not accidentally a period of the carrier frequency.

The fact that there is no relative delay between the signals that passed through the different ORRs is because the phase relation between the two different laser tones is not set correctly (as is done by the different lengths of waveguide). Only the slope of the phase response around the resonance point (around the modulated tone) is set correctly (see Fig. 4). The phase relation between the two tones will not, or barely, be changed by tuning the group delay function (tuning the coupling coefficient). The difference in induced phase shift over one FSR will always be 2π (see Fig. 1). It can be concluded that the complete SSB signal has to experience a flat group delay response in order to get the proper delay in the microwave domain. So in the case of using ORRs, the delay bandwidth must be wide enough for the entire optical signal, not only for the modulation bandwidth.

## Conclusion

It was concluded that a flat group delay response is needed over the entire range of the optical signal when using the tunable group delay of ORRs for the construction of OTTD networks. In other words, both optical tones and the modulation need to fit in the delay bandwidth of the ORR(s) to get the correct delay in the microwave domain. Some inconsistencies in the literature about this required delay bandwidth were pointed out. Simulations were presented that support the statement.

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