# All-Optical Discrete Fourier Transform for OFDM Demultiplexing and its Sensitivity to Phase Errors

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*Abstract*—**We present the design of an optical OFDM-demultiplexer for the separation of 8 sub-channels. Using simulations, we investigate the tolerance towards phase errors in the structure which could be realized as a planar lightwave circuit (PLC).**

***Keywords-Optoelectronic integrated circuits, Optical communications, Optical transforms, Multimode interference devices***

## I. INTRODUCTION

Latest experiments in the field of optical orthogonal frequency division multiplexing (OFDM) technology have shown the feasibility of a bandwidth-efficient and dispersion-tolerant optical transmission system at high data rates [1]. The corresponding structure for the discrete Fourier transform (DFT) or a computation efficient Fast Fourier transform (FFT) in the receiver as well as their inverse counterparts in the transmitter can be realized by various methods using optical delay interferometers (DI, [1]), arrayed-waveguide grating routers (AWGR, [2],[3]) or multimode interference (MMI) couplers [4]. In this paper, we present a new structure for an 8-channel OFDM demultiplexer which consists of 2×2 and 4×4 MMI couplers, delay lines and phase shifters. This two-stage layout with only a small number of couplers allows for compact device on a small footprint. After introducing the principles of operation, we investigate the impact of phase errors on the signal quality, *Q*. Using Monte-Carlo simulation, we evaluate how much phase deviation this DFT structure can tolerate without severe performance deterioration.

## II. OPERATION PRINCIPLES AND SIMULATION SETUP

The separation of one OFDM super-channel into *N* sub-carrier channels $X_0$ to $X_7$ is performed by applying a discrete Fourier transformation

$$X_m = \sum_{n=0}^{N-1} e^{-j2\pi\frac{mn}{N}} x_n, \quad m = 0, \ldots, N-1, \tag{1}$$

where $x_n$ represents the *N* equidistant samples of the incoming signal x(t) over a period of time *T*. Figure 1 shows the proposed design for an optical 8-point DFT circuit. The first stage consists of two symmetrical 2×2 MMI couplers and delay lines with a length difference of 4*T*, while symmetrical 4×4 MMI couplers are being connected by delay lines of length 0*T*…3*T* on each arm of the second stage. Additional tuning elements, denoted by $\varphi_{Ai}$ and $\varphi_{Bi}$, are used to adjust the phases. However, only phase differences between the delay lines change the behavior of the filter. The filter structure shown in Fig. 1 is similar to the DFT architecture presented in [5] except that we use multi-mode instead of slab coupler and resort the delay line order.

It should be noted that, in contrast to the electrical processing, this optical DFT is computed continuously. Instead of superimposing weighted, sampled signal values, we feed the signal and its delayed copies to the last MMI couplers in the upper and lower arm which perform the addition. Following these outputs, electro-absorption optical switches can be used as optical gates to perform the needed time gating.

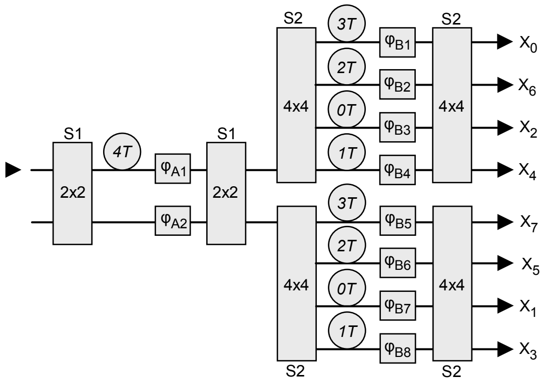

Figure 1. Structure for an 8 channel OFDM demultiplexer consisting of symmetrical 2×2 and 4×4 MMI couplers (labeled as S1 and S2), different delay lines (unit delay *T* is equal to the symbol period) and phase shifters.

Phase errors on the delay lines, caused by the manufacturing uncertainty or imprecise adjustment of the phase shifters result in a shift of the equidistant filter zeros. Consequently, the subcarriers are no longer orthogonal which leads to interchannel interference (ICI). In this context, a statistical analysis of the estimated filter sensitivity prior to the realization step is helpful for the design process.

We used VPItransmissionMaker$^{TM}$ 8.7 to evaluate the performance of the proposed OFDM demultiplexer statistically. Therefore, we feed 8 QPSK modulators, each transmitting with a symbol rate of 25 GSymbols/s, with a

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separate wavelength obtained from an optical comb generator. Pulse shapers with a rise time of 5 ps were implemented for smoothing the modulator driving signals. Since no cyclic prefixes were used, the carrier frequencies were spaced at the reciprocal value of the symbol duration, which is 40 ps, to fulfill the OFDM condition, i.e. the orthogonality of the signals. As our investigation is focused on the sensitivity of the DFT circuit to phase errors, we assumed an ideal transmission link without dispersion or noise impairments. The receiver at each output of the demultiplexer is modeled as an ideal 90° hybrid. Furthermore, each sub-channel receiver was set to perform a perfect clock and carrier recovery at the optimal sampling time.

In a Monte-Carlo simulation with 1000 iterations, we add phase errors to each delay line of the filter. These errors were assumed to be Gaussian distributed with mean values of zero and specific standard deviations. We then evaluated 256 transmitted symbols on each channel for every iteration step to determine the signal quality $Q$, which was derived according to the definition in [6]. Assuming Gaussian statistics, $Q$-values of 15.56 dB, 12.6 dB and 9.8 dB translate to bit error rates of $10^{-9}$, $10^{-5}$ and $10^{-3}$, respectively.

## III. RESULTS AND DISCUSSION

A comparison of system quality $Q$ versus the standard deviation of the phase errors can be seen in Fig. 2. The results have been averaged over 1000 iteration runs for every channel and every step of standard deviation. Due to rise and fall time limitations in the transmitter and receiver, the orhogonality condition is not perfectly fullfilled in this setup. Even an optimal phase adjustment in the DFT structure will lead to intersymbol and interchannel interferences and hence this will lower the $Q$-factor to around 15 dB to 17 dB. The resulting crosstalk on each channel increases the closer it is located to the center of the super-channel. With rising deviation from ideal phase conditions, the $Q$-factor decreases at a rate of ~2 dB every additional 5° phase error.

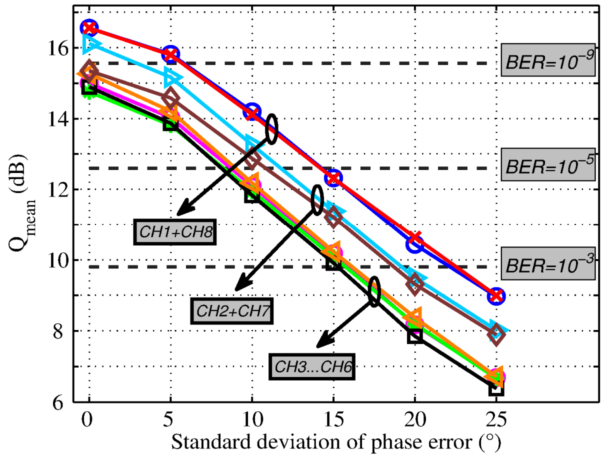

Figure 2. Mean $Q$ versus the standard deviation of applied phase errors.

The yield curves as a function of penalty tolerance are shown in Fig 3. Following the definition in [3], a yield of 100% means that all simulation runs from one specific set of phase errors with a certain standard deviation provide a system performance, $Q$, which is greater than a certain chosen boundary. Since we set this threshold to $Q_{\text{Limit}} = 9.8$ dB, the value for the yield at 2 dB penalty tolerance, for example, refers to the fraction of simulation runs with an $Q$-value larger than 9,8 dB – 2 dB = 7,8 dB. The results obtained in this simulation show that this filter structure is resilient against phase errors caused by imprecise adjustment of the phase shifters and manufacturing uncertainties. The advantage of this approach over other coupler-based alternatives is its compact design requiring lower number of delay lines. Consequently, there are less elements in the filter structure susceptible to phase errors.

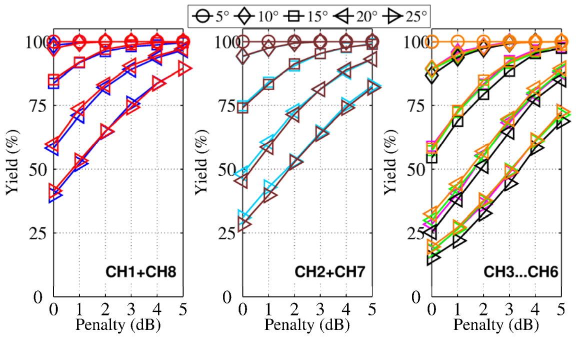

Figure 3. Yield curves versus acceptable penalty ($Q_{\text{Limit}} = 9.8$ dB).

## IV. CONCLUSION

We presented a new filter layout for an 8-channel OFDM demultiplexer which could be realized in planar waveguide technology. Using a Monte-Carlo simulation, the sensitivity to different sets of delay line phase errors was analyzed. It is shown that coupler based structures for OFDM application can be used, if properly designed with higher order MMI couplers, as an alternative to AWG realizations.

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