CHAPTER 2

LITERATURE REVIEW

2.1 OPTICAL DELAY LINE FILTERS

The implementation of fiber-optic lattice structures incorporating single-mode fibers and directional couplers was presented by Behzad Moslehi et al (1984). These fiber structures can be used to perform various high-speed time domain and frequency domain functions such as matrix operations and frequency filtering. They introduce the concept of lattice structure optical filters. Lattice structures are suitable forms for performing various signal processing operations. Compared to other forms, lattice structures have some advantageous characteristics, such as modularity, regularity, ease of implementation, and good sensitivity.

Single-mode optical fiber is an attractive delay medium for processing microwave frequency signals due to its extremely low loss (<0.1 dB/ps) and large available time-bandwidth product. The efficient coupling of light from single-mode fibers has made it possible to construct recirculating and nonrecirculating (tapped) delay-line structures that can perform a variety of important signal processing functions. These functions include coded sequence generation, convolution, correlation, matrix-vector multiplication, and frequency filtering. Kenneth P. Jackson et al (1986) presented the fundamental properties of single-mode fiber delay lines.

Kaname jinguji (1996) proposed a two port circuit configuration with ring waveguides which can realize the same filter characteristics as infinite impulse response (IIR) digital filters. This method is based on
scattering matrix factorization. They also provide synthesis examples which includes an elliptic filter, a Butterworth filter, an optical filter with maximally flat group-delay characteristics, a group-delay dispersion equalizer, and a multichannel selector.

A method for synthesizing a coherent two-port lattice-form optical delay-line circuit that is composed of optical delay lines, directional couplers, and phase shifters, was presented by Kaname Jinguji and Masao Kawachi (1995). They are based on a unimodulus para-unitary matrix as a transfer matrix and the division of the transfer matrix into basic component transfer matrices. They succeeded in obtaining a set of recurrent equations to calculate circuit parameters which is used for designing an optical delay-line circuit with a desired cross-port (through-port) transfer function. In the developed method, it is shown that two-port optical delayline circuits can have the same transmission characteristics as finite impulse response digital filters with complex expansion coefficients. It is also shown that the $N^{th}$-order complex FIR digital filters can be realized by $N$-cascaded, two-port lattice-form, optical delay-line circuits. In this case the numbers of directional couplers, delay lines, and phase shifters necessary to realize $N^{th}$-order all-zero filters are $N + 1$, $N$, and $N$, respectively. The use of excess directional couplers required in Kikuchi’s theory is overcome in this method.

Kishioka (2001) made the first attempt to design $N^{th}$ order optical filters using three-port optical delay-line circuits. A synthesis algorithm was proposed to design a filter with a wide wavelength-flattened response. In this, only one channel of transmission was designed to meet the desired response, while the transmissions of the other two channels are neglected.

Qi Jie Wang et al (2005) have devised a methodology for designing a general lattice filter that is made of an optical delay-line circuit to implement three-port optical interleavers. It consists of two parts of lattice
structures viz, N and two stages of $3 \times 3$ directional couplers linked by differential delay lines. By carefully choosing differential delay lines in the lattice structures, the resultant filter is capable of producing three channels of $2\pi/3$ phase-shifted interleaving transmissions and a recursive synthesis approach is used. Compared with the general optimization approaches, the proposed design scheme greatly reduces the computational efforts and improves the performance of the interleaver. It is also shown that by using the proposed synthesis approach, the optical interleaver can be prespecified with desired specifications on the transmission passband ripples, passband shape, and channel isolation.

Thus, the proposed optical delay-line circuit and the recursive synthesis approach constitute a systematic design scheme for a three-port optical interleaver design. The effectiveness of the proposed scheme is demonstrated by simulations through designing optical interleavers to achieve maximally flat-top transmissions, specified transmission with certain passband ripples, and certain passband bandwidth.

Kaname Jinguji and Takashi Yasui (2008) have presented a one-input M-output (1xM) circuit configuration for realizing optical FIR lattice circuits with output channels (M>2). The circuit configuration has a multilayer structure composed of MZIs with delay time differences of zero or $\Delta\tau$. The proposed synthesis algorithm is based on factorizations of the paraunitary total transfer matrix. It realizes output responses having highest orders equal to the number of stages for all output channels. It was shown that such a synthesis algorithm maximizes the degrees of freedom for designing output responses and can realize arbitrary FIR filter characteristics. Furthermore, they introduced circuit configurations having different phase shifter arrangements and briefly discussed their synthesis algorithm. Two kinds of five-channel interleave filters are demonstrated as synthesized
examples: namely a flat group delay response and an inclined group delay response.

Kikuchi et al (1990) have presented a coherent two-port lattice-form optical delay-line circuit synthesized without phase shifter. It was based on dividing total transfer matrix into product of transfer matrices expressing zero-order and one-order components.

Kaname jinguji and Masao Kawachi (1995) has presented a method for synthesizing a coherent two port lattice form optical delay line circuit that is composed of optical delay lines, directional couplers, and phase shifters. The two bases of the method are the use of a unimodulus para-unitary matrix as a transfer matrix and division of the transfer matrix into basic component transfer matrices.

They succeeded in obtaining a set of recurrent equations with which to calculate circuit parameters to use for designing an optical delay-line circuit with a desired cross-port (through-port) transfer function. In the developed method, it was shown that two-port optical delay line circuits can have the same transmission characteristics as finite impulse response digital filters with complex expansion coefficients.

Shafiul Azam et al (2007) have given a novel circuit configuration of an (1x3) optical delay-line circuit with same filter characteristics as those of a digital FIR filter. It has \( N \) stages that is composed of \( 2x(N + 1) \) directional couplers, \( N \) optical delay-lines, \( 2x(N + 1) \) phase shifters and one external phase shifter. This synthesis method was based on division of transfer matrix into the basic component transfer matrix. A set of recursion equations was derived to obtain the circuit parameters. In the developed method, it was shown that (1 \( \times \) 3) optical delay-line circuit has the same transmission characteristics as finite impulse response (FIR) digital filters with complex expansion coefficients.
Band-pass flat group delay type filter is considered as an example. It could be employed in FDM and WDM optical communication.

Shafiul Azam et al (2008) have proposed a 1-input 3-output optical delay-line circuit with IIR architectures that can realize any arbitrary three-port IIR optical filter characteristics. The synthesis algorithm is based on division of total transfer matrix into basic unit blocks i.e. repeated size reduction (factorization). A circuit configuration comprising Mach-Zehnder interferometer and all-pass ring resonator is proposed. A set of recursion equations were derived to obtain all unknown circuit parameters. A three-port IIR optical filter is synthesized via the design data of a three-port IIR digital filter. A sharp edge filter characteristic was achieved with almost 0 dB power transmittance at the pass band and -60 dB at the stop band. Compared with 1 x 3 FIR type delay-line circuit, this proposed 1 x 3 IIR type delay-line circuit offers sharp edge filter characteristics because of the feedback effect. The synthesis algorithm can be employed for various optical filters and optical adaptive filters in FDM and TDM optical communications.

A lattice-form interleave filter, representing a 1 x 2 delay-line circuit has been constructed from optical couplers and phase shifters using an established design algorithm by Jinguji and Oguma (2000), which is most attractive among the interleave filters. Based on this design a four-channel device was fabricated by cascading three 1 x 2 interleave filters (M. Oguma et al 2004). A 1 x 3 lattice-form interleave filter has been designed, in which 3 x 3 directional couplers with a triangle structure are employed (Wang et al 2005).

Kaname Jinguji and Takashi Yasui (2007) have proposed a one-input M-output (1 ×M) circuit configuration for an interleave filter with M output ports (M ≥ 2). A M-channel lattice-form interleave filter is an extension of the conventional interleave filter with two channels. The M-
channel interleave filter has $M$ output channels, each of which has a flat pass band with a bandwidth of one-$M^{th}$ of the FSR. The proposed synthesis algorithm was based on polyphase decomposition and yields circuit parameters ensuring that every output characteristic has an $M^{th}$-band property. A five-channel interleave filter was presented as an example of the design procedure.

A novel lattice optical delay-line circuit using $3 \times 3$ directional couplers to implement three-port optical interleaving filters was proposed by Qi Jie Wang et al in 2005. It was shown that the proposed circuit can deliver three channels of $2\pi/3$ phase-shifted interleaving transmission spectra if the coupling ratios of the last two directional couplers are selected appropriately. The other performance requirements of an optical interleaver can be achieved by designing the remaining part of the lattice circuit. A recursive synthesis design algorithm was developed to calculate the design parameters of the lattice circuit that will yield the desired filter response.

2.2 APPLICATION OF OPTICAL LATTICE CIRCUITS

Many applications of optical lattice circuits have been reported, including group-velocity dispersion equalizers, an adaptive gain equalizer, an interleave filter, an add–drop filter, and polarization mode dispersion compensators. A two-port lattice type optical delay-line circuit and an 1x 3 optical delay-line circuit that can realize 100% power transmission is reported.

Marc Bohn et al (2004) have presented an adaptive equalization of chromatic dispersion, self-phase modulation, and polarization mode dispersion with integrated optical finite impulse response filters. A synthesis approach to determine the complex filter coefficients of nonrecursive DLF for dispersion and dispersion-slope compensation has been proposed by Thomas
Duthel (2006). In their work, the dispersion of the DLF for the requirements of the transmission channel is optimized instead of optimizing all the filter coefficients to obtain the inverse channel response.

Thomas Duthel et al (2004), have proposed an all-fiber second-order optical delay line filter for dispersion compensation in optical networks with channel bit rates of 40 Gb/s. Secondini et al (2003) have presented an adaptive optical equalizer for chromatic dispersion compensation, based on planar lightwave circuit (PLC) technology and controlled by a minimum mean square error (MSE) strategy.

Integrated optical all-pass filters have been presented that can be used for tunable dispersion compensation, dispersion slope compensation, and as building blocks in tunable band pass filters. The dispersion slope compensation capability is demonstrated using ring resonators by Madsen et al (1999).

Electrical equalization of CD, Self-Phase Modulation (SPM), and Polarization Mode Dispersion (PMD) with finite impulse response (FIR) and decision feedback equalizers (DFEs) that minimize the intersymbol interference (ISI) and Viterbi equalizers based on maximum likelihood sequence estimation (MLSE) has already been proposed. Various components for tunable chromatic dispersion compensation have been proposed. They include fiber-optic solutions such as dispersion-compensating chirped fiber Bragg gratings (DCFBG), free-space optics such as virtually image phase arrays (VIPA), and integrated infinite impulse response (IIR) and FIR filters such as cascaded etalons, cascaded ring resonators, and cascaded Mach–Zehnder interferometers (MZIs).

Many implementations of optical FIR filter for signal processing applications have been realized in integrated photonics using couplers. Rahim
et al (2012) implemented a filter using 4× 4 couplers. Such a filter is useful for the compensation of residual dispersion in fiber-optic transmission system. Silicon photonics realization using 4-port multimode interference couplers in 4µm silicon-on-insulator technology has been carried out for a free spectral range of 100 GHz. The transmission and group delay for the fabricated device have been measured and a good agreement between the simulation and experimental results has been achieved. The filter has compensated up to ±176ps/nm of fiber chromatic dispersion. To prove the concept, they fabricated a two-stage parallel–serial filter using 4x4 Multimode Interference (MMI) couplers in 4µm SOI platform. The fabricated device has been characterized for transmission and group delay. It has been found that the fabricated filter provides residual dispersion compensation for 28 Gbaud QPSK transmission systems and introduces an OSNR penalty of only 0.34 dB.

A filter using generalized MZIs for tunable residual dispersion compensation was presented by Rahim et al (2012). They gave the design, silicon photonic realization and its characteristics. It is realized that a tunable filter in silicon photonics for the compensation of residual dispersion using Generalized Mach Zehnder Interferometers (GMZIs). This filter uses a chain of GMZIs. Higher order couplers are the key component to realize GMZIs. Progress in the field of silicon photonics has enabled higher order Multi-mode Interference (MMI) couplers with small excess loss, low imbalance and small phase errors over the C band. The filter has shown small group delay ripple of ±3ps and can compensate residual dispersion of up to ±180 ps/nm for multiple channels of 100 GHz optical WDM transmission system.

Gade et al (2012) presented a work in which cheap laser sources were used to generate the input chirped signal for cost efficient monitoring of optical access networks by using optical FMCW radar systems. They
presented a method to fully compensate for chirp nonlinearities in optical FMCW. By approximation of the chirp nonlinearity and applying the proposed algorithm, the chirp nonlinearity can be removed out of the beat spectrum leading to exact target positions. Due to this post processing method it is possible to use cost efficient direct modulated DFB laser sources without any linearization hardware effort or pre-compensation methods. Optical FMCW in combination with chirp nonlinearity compensation is an effective tool for preventative optical access network diagnosis which provides high range accuracy. It also brings the opportunity to react on performance degradations, e.g. by sending technicians to the exact fault position, before a network link is completely disrupted. The proposed approach increases the range accuracy significantly hence reducing the cost of maintenance in a long range optical access network considerably.

Gade et al (2011) presented a simple design of an adaptive dispersion slope compensator. In this article, a cascaded structure consisting of one symmetric and one asymmetric MZI has been analytically described. Both the measured bandwidth and achievable dispersion slope values corroborates the simulation results. The adaptability of the device has shown that second order dispersion of up to 1200 km standard single mode fiber can be compensated with this filter. Due to the periodicity of the filter function full adaptive dispersion slope compensation for multi channel WDM systems at bitrates of 40Gbps and above is possible.

Vestigial sideband filtering can be used for chromatic dispersion measurements. An optical delay line filter providing upper sideband (USB), lower sideband (LSB), and passband was designed for such application. The straightforward utilization is to measure the time delay between the USB and the LSB. A more practical approach is to estimate the chromatic dispersion (CD) by multiplying the USB and LSB signals in an electronic mixer and
filtering out the DC component of the resulting signal. This approach was successfully demonstrated by experiments at a data rate of 10 Gbit/s by Neumann (2011). Furthermore, the properties of the optical filter influence (e.g., filter extinction) were assessed by numerical simulations.

Geyer et al (2010) analyzed digital nonlinearity compensation and proposed a simplified compensator with an automatic control scheme. Two promising methods have been analyzed the use of a simplified nonlinear Volterra equalizer and back-propagation using the split-step Fourier method. Both have the problem of high implementation complexity and the latter also lacks a simple control scheme. Back-propagation seems to be unfeasible with current technology because splitting of the linear CD equalizer increases the complexity almost linearly with the number of equalizer elements. The proposed simple nonlinear compensator requires considerably lower implementation complexity and can blindly adapt the required coefficients. In uncompensated links, the simple scheme is not able to improve performance, as the nonlinear distortions are distributed over different amounts of CD-impairment. Nevertheless, the scheme might still be useful to compensate possible nonlinear distortions of the transmitter. In transmission links with full inline compensation the compensator provides 1dB additional noise tolerance. This makes it useful in 10Gbps upgrade scenarios where optical CD compensation is present.

The paper “Optimization of the chromatic dispersion equalizer of a 43Gbps real time coherent receiver”, Geyer et al (2010) explains a fifteen tap equalizer filter of a 43Gbps coherent polarization multiplexed QPSK receiver and provides a comparison of simulation results with measurements using an FPGA-based real time receiver. The ADCs have a resolution of 3bit and a sample rate of 21.5GS/s. Four Altera Stratix II GX FPGAs are used for the
processing. With this setup it is not possible to process the whole 43 Gbps data-stream. Therefore a block-processing scheme is used, which aggregates data blocks of 4096 symbols and processes one out of 32 blocks. The CD-equalizer uses finite impulse response filters with 15 complex tap coefficients. The PMD equalizer filters consist of seven taps each, which are adapted by a least-mean-square algorithm. Optimization extends the chromatic dispersion tolerance from 4,000ps/nm to 7,000ps/nm.

Geyer et al. (2009) presented Optical Performance Monitoring from the equalizer filter setting of an FPGA-based real time 43Gbps Polarization Diverse Coherent Receiver. Chromatic Dispersion and Polarization Mode Dispersion of the optical transmission link are independently estimated from the blindly adapted equalizer filter. Usually an adaptive filter, controlled by a blind least mean squares algorithm is used to compensate for chromatic dispersion, polarization mode dispersion (PMD), polarization dependent loss (PDL) and polarization transformations of the link. The accuracy of the estimates is demonstrated based on measurements. Despite limited vertical resolution in the ADC and finite filter tap length the channel parameter estimates are extremely accurate. The calculated data can be used to provide in-service estimates of chromatic dispersion and differential group delay in future transmission systems in order to maintain high system performance or react to parameter degradation.

Neumann et al. (2007) introduced a simple fiber optical filter for dispersion monitoring using the dispersion-induced electrical phase shift of the received upper and lower sideband signals and presented proof-of-concept measurements in a 10G system. A second order fiber optical delay line filter that couples out the USB and LSB of a 10Gbps NRZ signal and allows the data signal to pass through is designed. Here a fiber optical delay line filter
was introduced to couple the upper and lower side band of a signal and pass through the signal at the same time on the third output port. This simple filter is possibly cheap, easy to manufacture and usable in WDM systems. They demonstrated the functionality of the filter in a proof-of-concept measurement that showed encouraging results. There is a significant increase of the accuracy when the phase shift of the recovered clock of the USB and LSB or the cross correlation between USB and LSB are evaluated.

Hauske et al (2008), presented a robust and precise optical performance monitoring technique from FIR filter coefficients in coherent receivers with digital equalization. The filters are blindly adapted based on measured data with off-line processing on a PC. Residual chromatic dispersion, Differential Group Delay (DGD) and Optical Signal-to-Noise Ratio (OSNR) are simultaneously estimated from measured 111 Gbit/s data. As long as the required channel memory is lower than the total filter length the estimation follows a monotonous function, which is nearly independent from the kind and the degree of the distortion. With a normalized abscissa the OSNR could be estimated with a precision of ±1 dB. In the case of CD = +1500 ps/nm, the channel memory almost equals the filter length. So the update signal contains deterministic signal components, which cannot be equalized for.

In this case the function starts to be shifted by a certain offset. The offset even increases for higher values of CD. The estimation is accurate over a wide range from −2000 ps/nm to +2000ps/nm in steps of 250ps/nm. For ±2000ps/nm the channel memory spreads over more than 12 symbol durations, which is longer than the filter length. Still the estimation delivers a precise value with a slight under-estimation. The highest standard deviation obtained for variations of the input OSNR from 12 dB to 24 dB was ±63ps/nm at CD = −1500ps/nm. The combined effect of strong CD of
1000ps/nm and DGD values of 0ps, 30ps, 60ps and 90ps is demonstrated. The excellent estimation of the CD value, which is carried out first in the Optical Performance Monitoring routine, leads to a high accuracy of the DGD estimation. This proves, that the separation of both effects works well. Again, a low standard deviation for both parameters for variations of OSNR from 12 dB to 24 dB is shown. Equally good results were obtained from filters with 11 and 31 taps.

A new approach to calculate filter coefficients by applying analytical methods was presented by Neumann et al (2007). Due to the time-variant property of the dispersion, those filters have to be adaptive, which requires fast and reliable calculation of the filter coefficients. A new method to straightforwardly calculate the coefficients of optical delay-line filters without using MSE approaches has been shown. The filter performance was simulated and discussed. In addition, design examples for the important scenarios of dispersion compensation and dispersion slope compensation were given.

All optical delay line filters can be used to compensate chromatic dispersion. The usual iterative method to determine the filter coefficients often leads to non-optimal results. In the case of optical delay line filters, the interference between registers as in digital signal processing is not considered. Here, it is important that the length of the longest delay line is shorter than the coherence length of the used light source. Based on the analogy of optical delay line filters and digital filters, the phase response, group delay and dispersion of a zero with respect to its radius and phase could be found. Finally, using the Fourier series representation of the dispersion function, a filter with a saw tooth-shaped dispersion could be designed. The analytic approach for the filter design was presented by Neumann et al (2011). These
approaches lead to equations that are difficult to solve. Techniques to make these computations easier are discussed.

A quasi-analytic synthesis algorithm was presented by Duthel (2006) to determine the coefficients of nonrecursive optical delay line filters with approximately constant or linear dispersion. The synthesis of the coefficients is based on a rigorous analysis of the impact of transfer function on the filter's dispersion behavior. The abilities of the synthesized filters are proven in system simulations at 40 Gbps. Therefore, filters of different orders were investigated in the static case (i.e., with a fixed dispersion) and the dynamic case. The advantages of this algorithm are that filters of arbitrary order have similar dispersion shapes and that the dispersion values of the filters can be adjusted by controlling a single parameter instead of optimizing all the filter coefficients independently. The realized dispersion shapes are reproducible, and no iterative algorithms are needed for the calculation.

Multi-channel residual dispersion compensation in a 40 Gbit/s optical transmission system with 100 GHz channel spacing using a single adaptive all-fiber delay line filter was presented and the device was based on 3×3 fiber couplers. This residual dispersion is not constant and varies due to temperature or other environmental changes along the link. In order to reduce the costs of residual dispersion compensation per channel it is desirable to compensate several channels simultaneously. This can be accomplished due to the slowly varying character of the residual dispersion versus the wavelength. Periodic filters with an appropriate free spectral range (FSR) are suitable for this task. These delay line filters can have recursive or non-recursive structures, which are generally implemented in planar- or bulk-optics.

Duthel et al (2004) deals with optical networks with channel bit rates of 40Gbit/s or higher chromatic dispersion is a severe limiting factor.
The main part of the chromatic dispersion is usually compensated by dispersion compensating fiber, however a small amount of dispersion always remains due to, for example, rerouting or temperature variations. This residual dispersion has to be compensated adaptively to guarantee that the dispersion stays within the tolerant range of the receiver. For this purpose several approaches have been introduced. The most common solutions are tunable chirped fiber Bragg gratings and optical delay line structures in planar- and bulk-optics. The capabilities of recursive and non-recursive delay line structures have been proven in system experiments. These components suffer from high loss due to fiber coupling and furthermore, planar devices are polarization sensitive. In this paper, residual dispersion compensation with an all-fiber delay line filter is successfully demonstrated in 40Gbit/s system experiments. The device is continuously tunable in the range of ±50ps/nm. Its major advantage is the simple structure and that the dispersion is controlled by changing only one parameter. To the best of our knowledge this is the first experiment utilizing an all-fiber delay line filter for dispersion compensation.