Design and Implementation of Microwave Photonic Filter

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Approval

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Abstract

Microwave photonic filter (MPF) has been a topic of interest for many years because of various advantages including large operational bandwidth, wide-ranging tunability, less losses and immunity to electromagnetic interference. These features are difficult to realize in electronic domain. MPF can be implemented in coherent and in-coherent regime, but coherent regime is severely limited by environmental conditions hence in-coherent regime is preferred. MPF in in-coherent regime is based on multiple wavelengths and dispersive element, however it is not a practical approach to use a separate laser source for each tap. To resolve this issue, single continues wave (CW) based generation of multiple wavelengths are used. In this thesis we have proposed an optimal and low-cost way of generating multiple wavelengths via modulating RF signal with optical carrier along with optical carrier suppression technique. We have validated our technique using 3 and 4 taps microwave photonic filter which are mentioned in Result section.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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Signature: ________________

Dedication

Dedication of this thesis goes to my parents and other family members, who supported me throughout the way up to this step and encouraged me whenever I would fall, and prayed for me all the time, I would have not been writing these words without their support and encouragement. May Allah give them long live with good health.

I specially dedicate my thesis to my honourable advisor, Dr Salman Abdul Ghafoor, being very cooperative, and a best source of knowledge for me. I am able to write this work only because of his efforts, and courage, which made me so excited to come up with this document, his kindness and attention with me an my work are admirable. May Allah grant him best of the best in the world and world after this.

Dedication of this thesis also goes to my sweet friends as well (Special Thanks to Malik Anas Ahmad), who all the time supported me in every situation, while knowing that I was wrong sometimes, and they always have been a source of enjoyment for me, whenever I needed people around me, I found them all the time around me, and always prayed and wished for my success. I am very grateful to them, and I really appreciate all of them for being very kind to me.

Acknowledgment

All praise to Allah Almighty, who gave me life, knowledge and kept me healthy for completing this thesis work, without the blessings of Allah, it was not possible for me to come up with this work.

I admire the contribution of my beloved advisor, Dr Salman Abdul Ghafoor, for his tremendous efforts towards my thesis work, his immense knowledge brought me explore the problem, mentioned in the title, in a very delightful manner, and I am very grateful to my other committee members whose continues support, motivation, knowledge, and guidance made me able to complete my thesis work with desired results.

Thanks to National University of Science and Technology (NUST) and I am proud to be student of NUST, such a best institute I have ever seen. All around I see every thing on its peak from faculty to other staff members, clean and pleasant environment adds more beauty to the profile of NUST. May Allah keep it safe and sound. I would like to acknowledge and appreciate the supportive behaviour of SEECS administration and staff, who never say no whenever they are requested for some help and guidance.

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Chapter 1

Introduction To Thesis

1.1 Background

Extensive research has been done in the domian of microwave photonic where microwave photonics covers study of generation, processing, transmission, detection of microwave and millimeter waves by mean of photonic devices. One of the attractive application is microwave photonic filtering because of their features like low losses, immunity to electromagnetic interference, wide tunability and reconfigurability. In traditional approach of RF, it is very difficult to realize such advantages hence a lot of techniques have been proposed based on coherent and in-coherent regimes. The filter based on in-coherent regime offers stable behavior against environmental conditions due to in-coherent operation of laser system and eliminates the problem of optical interference at the output [1]- [8].

A microwave photonic filter(MPF) is based on photonic devices and the

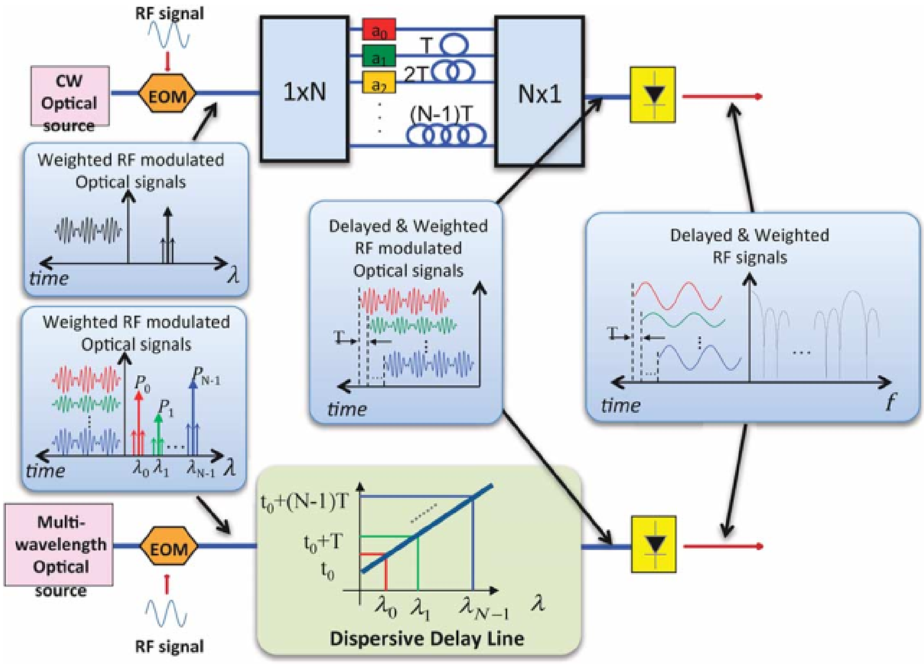


Figure 1.1: Two technical approaches of Microwave Photonic Filter based on FIR [7].

aim of the filter is to replace the standard microwave filter due to numerous advantages that have been highlighted in previous paragraph. The general layout of microwave photonic filter (MPF) is shown in Fig. 1.1. The conversion of RF signal into optical domian is done directly modulating or externally modulating either by single continuous wave laser source or continuous wave laser source array. Input RF signal is modulated with optical carrier and then applied to photonic circuit, where multiple copies of weighted and delayed samples of composite signal are generated in optical domain to realize two manin digital filtering techniques i.e. finite impulse response(FIR) and the other one is infinite impulse response (IIR). At output these samples are combined by optical delay lines at photodetector to recovered RF signal.

The conversion of RF signal into optical and again optical in to RF signal at modulator and photodetector respectively, is a nonlinear process, however overall linearity can be achived under special cricumtances [7].

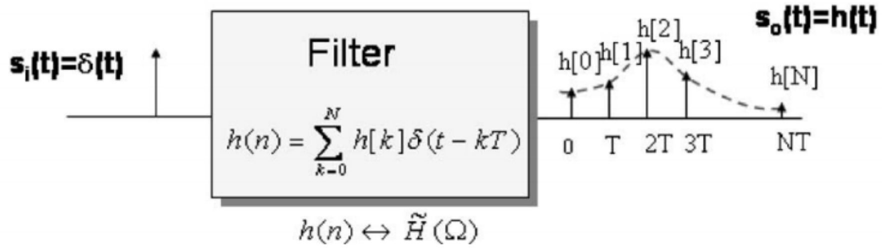


Figure 1.2: Impulse Response of Filter [3].

The equivalent impulse response $h(t)$ of microwave photonic filter (MPF)is presented in Fig. 1.2 can be mathematically expressed as,

$$S_o(t) = \sum_{r=-N}^{N} a_r S_i(t - rT) = S_i(t) * h(t) \tag{1.1}$$

$$h(t) = \sum_{r=-N}^{N} a_r \delta(t - rT) = \sum_{r=-N}^{N} h(t)\delta(t - rT) \tag{1.2}$$

Where $S_i(t)$ and $S_o(t)$ are the RF input and output signals respectively. MWP can be classified on the basis of number of samples N. If the total number of taps or samples are $N < \infty$ then the configuration is finite impulse response (FIR) while infinite impulse response (IIR) configuration if $N > \infty$.

The impulse response $h(t)$ can be considered as discrete-time signal. In such case the $z - transform$ and discrete-time Fourier transform can be given as,

$$H(z) = \sum_{m=-\infty}^{\infty} h(n) z^{-n}$$

$$H(\Omega) = \sum_{m=-\infty}^{\infty} h(n) e^{-jn\Omega T} \tag{1.3}$$

The microwave photonic filter in term of difference equation can be expressed as,

$$H(z) = \frac{S_o(z)}{S_i(z)} = \frac{\sum_{m=o}^{M} b_M z^{-m}}{1 + \sum_{n=1}^{N} c_N z^{-n}}$$

$$= \frac{N(z)}{D(z)} = \frac{\Gamma z^{N-M} \prod_{m=1}^{M} (z - z_M)}{\prod_{n=1}^{N} (z - p_N)} \tag{1.4}$$

In Eq 1.4 the transfer function is expressed in term of two polynomial ,i.e, $N(z)$ and $D(z)$. Both represent the filter poles and zeros respectively. The location of poles and zeros specify the response of filter while the values of poles and zeros are dependent on coefficients b_i and c_j.

The transfer function in Eq 1.3 shows that the transfer function of microwave photonic filter is periodic with period T. This period is also known as free spectral range (FSR) as shown in Fig. 1.3.

The bandpass functionality can be judged by full width half maximum ($\Delta\Omega_{FWHM}$), which is known as the 3-db bandwidth. The selectivity of band-

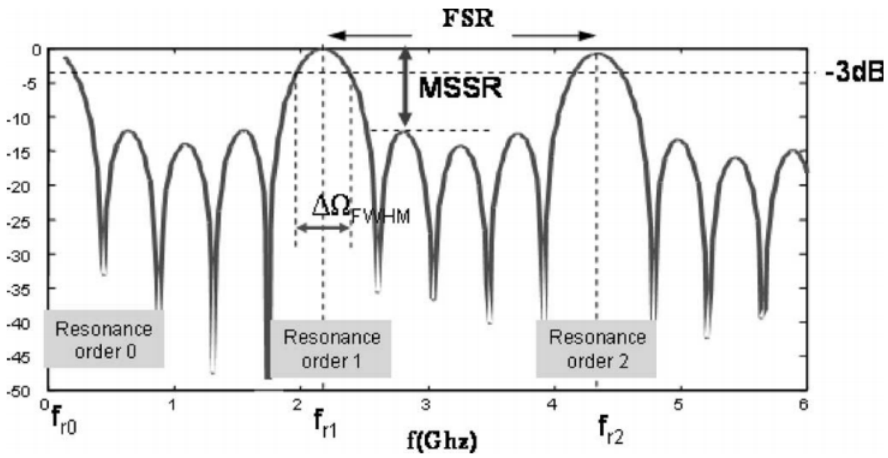


Figure 1.3: Impulse Response of Filter [3].

pass filter can be detemined as quality factor Q as,

$$Q = \frac{FSR}{\Delta\Omega_{FWHM}} \tag{1.5}$$

The Q factor is depended on number of taps or samples taken to implement filer. Higher the number of samples, the more narrower the passband will be. Finally, the measurement of rejection of non-adjacent channels by main to secondary sidelobe ratio (MSSR) is shown in Fig. 1.3.
The microwave photonic filters can be classified into single source or multiple source.

1.1.1 Single-Source Based Microwave Photonic Filters (SSMPF)

As the name suggest, only one optical source is used in Single Source Based Microwave Photonic Filters (SSMPF). The electric field generated by single source is given as,

$$\sqrt{I_i} e^{j(\omega_o + \phi_t)} \tag{1.6}$$

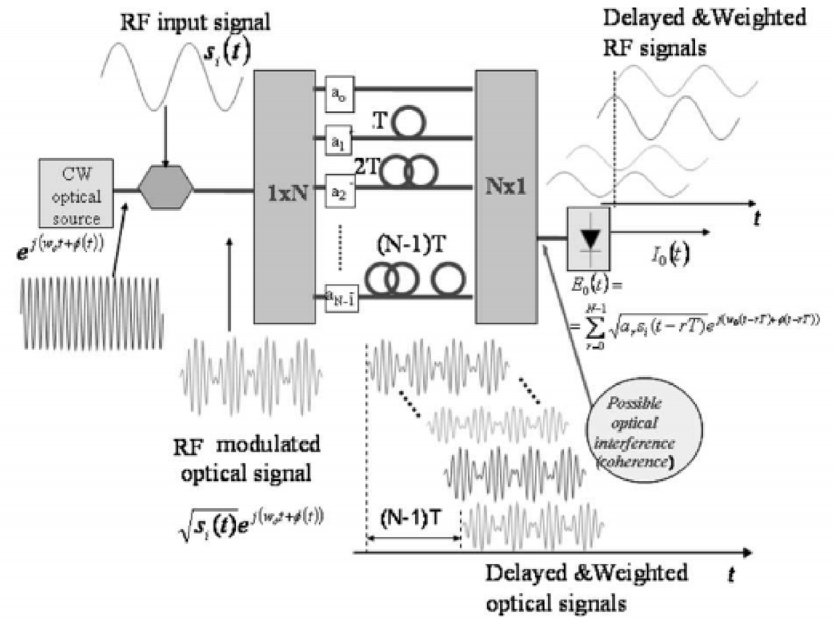
Where I_i is the optical intensity,the ω_o source frequency and ϕ_t phase fluctuations. The CW laser source is modulated with input RF signal S_i. The multiple samples are realized by introducing delays in replicas of RF modulated optical signals. There are two possible schemes to implement SSMPF as shown in Fig 1.4 (a) and (b) based of FIR and IIR configuration respectively.

In Fig 1.4 (a), the RF modulated electric field is evenly divided into N optical fibers via $1\chi N$ coupler. The length of each fiber is varied to achieved the basic time delay T between replicas of RF modulated optical signal. All the delayed signals are combine by $N\chi 1$ coupler and feed to photodetector to recover RF signal S_o. The output electric field is composed of interference from all samples.

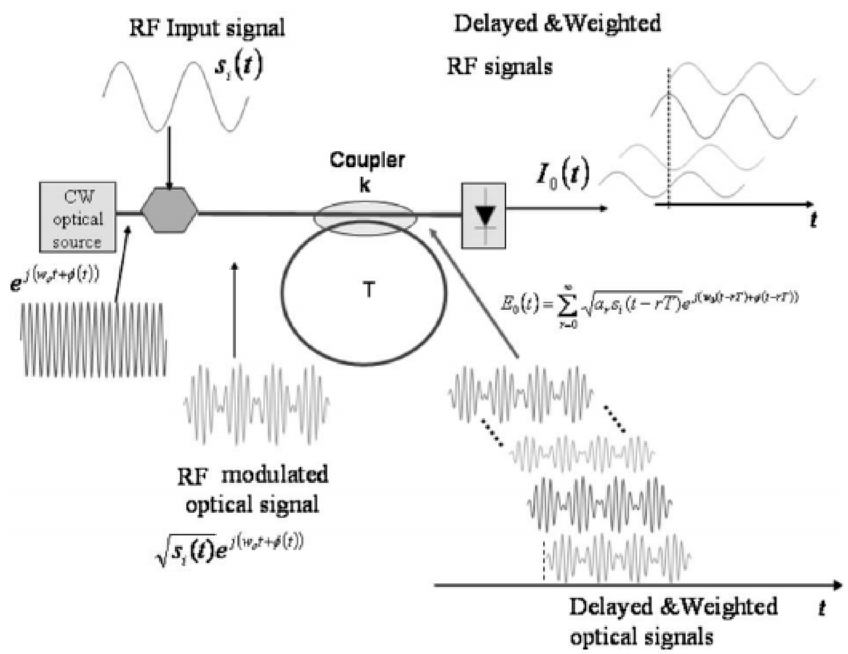
In Fig 1.4 (b), to generate infinite samples, single ring cavity recirculating delay line is realized by connecting two output ports of fiber coupler. A basic delay of T is generated in each recirculation.

Mathematically the output electric field for both operations can be expressed as,

$$E_o(t) = \sqrt{I_i} \sum_{r=o}^{N-1} [a_r s_i(t - rT)]^{\frac{1}{2}} e^{j(\omega_o(t-rT)+\phi(t-rT))} \tag{1.7}$$



(a)



(b)

Figure 1.4: (a) Layout of SSMPF based on FIR (b) Layout of SSMPF based on IIR [3].

The upper limit N will be finite in case of FIR, while infinite in case of IIR. The resultant output current generated by photodetector is given as,

$$\begin{aligned} I_o(t) &= \Re\langle|E_o(t)|^2\rangle \\ &= \Re I_i \sum_{r=o}^{N-1}[|a_r|s_i(t-rT)] \\ &+\Re I_i \sum_{r=o}^{N-1}\sum_{s\neq r}^{N-1}\sqrt{a_r a_s^* s_i(t-rT)s_i(t-sT)} \\ &\times\Gamma((r-s)T) \end{aligned} \tag{1.8}$$

Where $\Re$ is the responsivity of photodetector (detail in Section 2.8 Photodetector), while $\langle\rangle$ represents the ensemble average over phase noise of source and Γ represents the degree of coherence of source. This phase noise is considered stationary and can be modeled as Ergodic process,

$$\Gamma((r-s)T) \propto e^{-\dfrac{|(r-s)T|}{\tau_{coh}}} \tag{1.9}$$

$\tau_{coh} = 1/\pi\Delta v$ is coherence time of source. It is inversely proportional to laser line width Δv prior to modulation. Where the coherence time is the time over which the laser is considered to be coherent or in other-words this is the time over which the phase of laser is predictable. In Eq. 1.8, the output current generated by photodetector is comprise of two terms. The incoherent term in which output generated current can be linearly related to applied RF signal while the other coherent term is based on source degree of coherence.

If the coherence time of source is very small then basic time delay ($\tau_{coh} \ll T$) then the second expression in Eq. 1.8 will be zero, resulting in linear relation between applied and output RF signals as,

$$I_o(t) = s_o(t) = \Re I_i \sum_{r=o}^{N-1} [|a_r| s_i(t - rT)] \tag{1.10}$$

Microwave photonic filter based on above expression doesn't depends on optical phase fluctuations and are called incoherent MPF. These filters are highly stable due to non dependence of phase noise hence widely used.

If ($\tau_{coh} \gg T$) then the filter operate in coherent regime. The Eq. 1.9 can be expressed as,

$$\Gamma((r - s)T) = e^{j\omega_o (s-r)T} \tag{1.11}$$

The Eq. 1.8 can be re-written as,

$$s_o(t) = \Re I_i \sum_{r=o}^{N-1} [|a_r| s_i(t - rT)]$$

$$+\Re I_i \sum_{r=o}^{N-1} \sum_{s \neq r}^{N-1} \sqrt{a_r a_s^* s_i(t - rT) s_i(t - sT)} e^{j\omega_o (s-r)T} \tag{1.12}$$

The above expression clearly shows the filter is phase sensitive and hence coherent SSMPF are not implemented in practice.

1.1.2 Multiple-Source Based Microwave Photonic Filters (MSMPF)

MSMPF operates in in-coherent regime and as the name suggests, instead of using single optical source, multiple optical sources are used. The advantage of using multiple source will results in omission of coherence noise which was a problem in previous scheme based on single source. There are various ways to implement MSMPF ,i.e, an independent array of lasers can be used but it is costly. Broadband source can be used which will be converted into multiple wavelength by spectrum slicing however it will introduce amplitude noise in generated wavelengths. One other approach is Fabry–Pérot laser diode but in this scheme the power distribution inside cavity is not uniform which will limit the performance of filter.
Regardless of the schemes used to generate multiple wavelengths, the electric field prior to modulation is given as,

$$E_o(t) = \sum_{r=o}^{N-1} \sqrt{I_r} e^{j(\omega_r t + \phi_r(t))} \tag{1.13}$$

where I_r, ω_r and ϕ_r represents the optical intensity, frequency and the phase of source variations of rth laser respectively. The laser source act as a filter sample and the delay between samples is achieved by single mode fiber (SMF). The optical fiber is used as a dispersive element which offers group delay experienced by adjacent wavelength (samples) is T. The two main schemes to implement MSMPF based on FIR are shown in Fig. 1.5. The Fig. 1.5(a) shows the implementation of an FIR MSMPF using a laser array while Fig. 1.5(b) shows layout of an FIR MSMPF using a broadband source with dispersive elements.

The output electric field applied at photodetector is given as,

$$E_o(t) = \sum_{r=o}^{N-1} \sqrt{a_r s_{in}(t-rT)} e^{j(\omega_r(t-rT)+\phi_r(t-rT))} \tag{1.14}$$

While the current generated from photodetector to applied electric field is given as,

$$\begin{aligned} I_o(t) &= \Re\langle |E_o(t)|^2 \rangle \\ &= \Re \sum_{r=o}^{N-1} [|a_r| s_i(t-rT)] \\ &+ \Re \sum_{r=o}^{N-1} \sum_{s \neq r}^{N-1} \sqrt{a_r a_s^* s_i(t-rT) s_i(t-sT)} \\ &\times e^{j(\omega_r-\omega_s)t} e^{j(s\omega_s - r\omega_r)T} \langle e^{j[\phi_r(t-rT)+\phi_s(t-sT)]} \rangle \\ &= \Re \sum_{r=o}^{N-1} [|a_r| s_i(t-rT)] \end{aligned} \tag{1.15}$$

The second term vanishes from above mentioned expression since the variation in phase is assumed to be uncorrelated from different optical sources, hence a linear relationship is achieved between input and output.

The filter response can be made tunable in two ways by either changing wavelength separation between adjacent wavelength or by changing the length of fiber as shown in Eq. 1.16.

$$T = DL\Delta\lambda \tag{1.16}$$

Where D (ps/nm km)is dispersive parameter of fiber, L is the length of

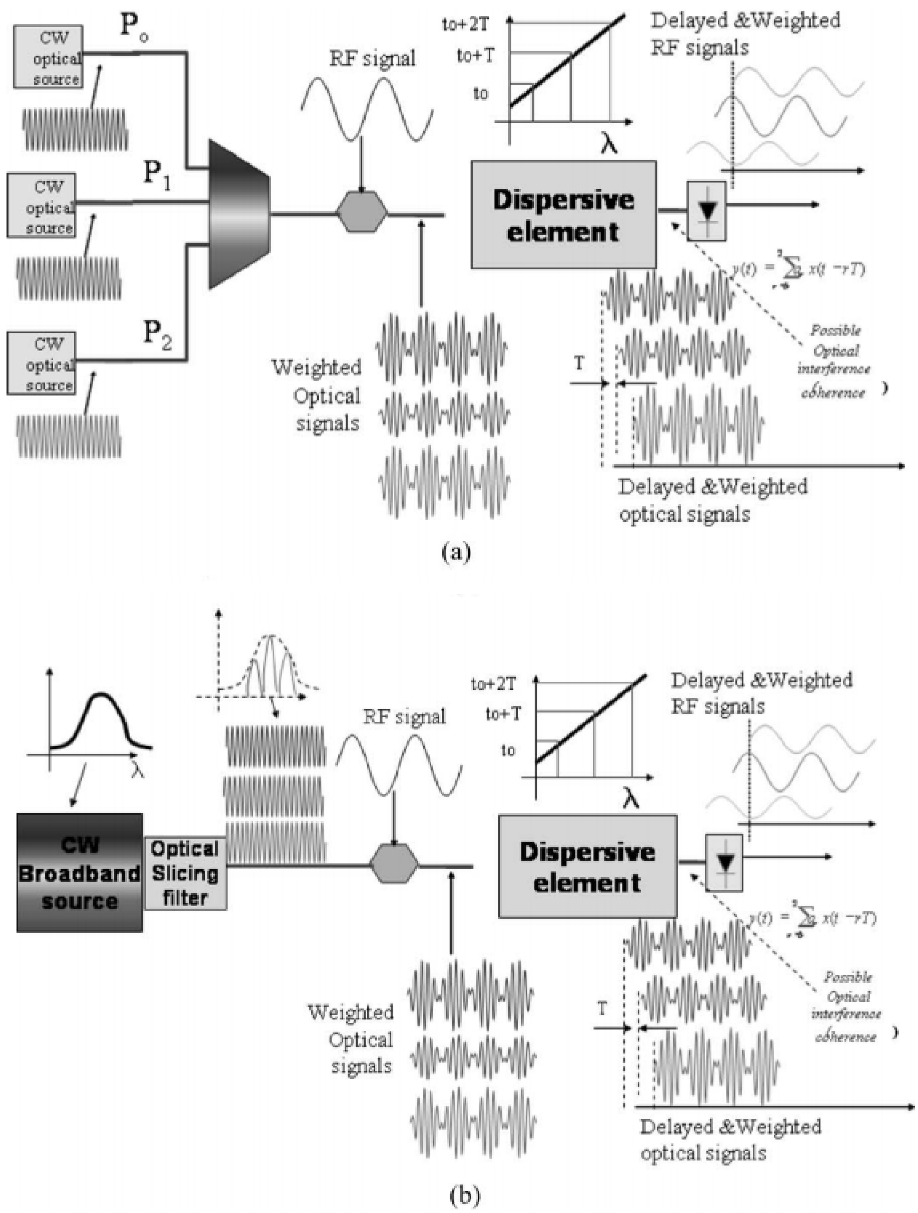


Figure 1.5: (a) Layout of FIR MSMPF based on laser array (b) Layout of FIR MSMPF based on Broadband source [3].

dispersive fiber and $\Delta\lambda$ is the wavelength separation between adjacent wavelengths. For single mode fiber (SMF) the dispersion D is 17 ps/nm km. If fiber of length 10 km and wavelength separation $\Delta\lambda$= 0.735nm is selected then according to Eq. 1.16, the time delay will be equal to T = 125ps and FSR of 8GHz [2]- [3].

Different parameters are varied to achieve different functionalities of microwave photonic filter like reconfigurability, selectivity and tunability. The N represents the number of samples or taps which shows either the filter is bandpass ($N > 2$) or a notch filter ($N = 2$). Tunability is the property of microwave photonic filter which enable the possibility of tuning the RF bandpass position, which is done by varying FSR. The filter response can also be tuned by varying phase via RF phase shifter. The reconfiguration is the property of filter which refer to dynamically modifying the magnitude of the taps to re-shape filters response and at the end the selectivity, which is based on quality factor Q and main to secondary sidelobe ratio (MSSL) these parameters are also determined by number of taps and their magnitude [4].

1.2 Motivation

As previously discussed, microwave photonic is the study of interaction between microwave and photonic technologies. Microwave photonic covers application areas such as sensor networks, wireless communication, wireless access networks, generation of microwave and mm-wave signals, phase arrayed antenna, satellite communication, photonic beam streaming, universal mobile telecommunication systems (UMTS) in order to fix access pico-cellular networks including wireless local area networks (WLAN), radio over fibre system, wavelength division multiplexing (WDM) and analogue to digital conversion etc. In short, the basic aim of microwave photonic filters are to replace traditional microwave filters. Keeping in view of above mentioned vast application areas, it is required to made the design of microwave photonic filter as optimal as it could be.

1.3 Problem Statement

Majority of the microwave photonic filters are design in in-coherent regime based on FIR. The main problem in this technique is having separate laser source for each taps which is not practical approach. In past few year different techniques have been proposed to sort out this problem but they have different limitation in practical deployment. We proposed generation of multiple wavelengths based on single continues wave laser.

1.4 Structure of the Thesis

The thesis is based on the following chapters: Chapter No. 1 has provided a comprehensive background of Microwave Photonic Filters and its applications.

In Chapter No. 2, discuss the basic of optical devices. This chapter also cover the phenomena of Four Wave Mixing, Optical Carrier Suppression Technique, Stimulated Brillouin and Raman Scattering and Fiber Bragg grating etc.

In Chapter No. 3, we will perform literature review, what has been down in recent years in the field of microwave photonic filters.

In Chapter No. 4, we will discuss in detail the proposed design of microwave photonic filters based on single continuous wave laser and optical carrier suppression technique. This chapter will also discuss the results we achieved through this research.

In Chapter No. 5, we draw conclusions and propose some future directions.

Chapter 2

Basics of Optical Devices

This chapter discuss the basic working principals of optical devices. The chapter also covers the phenomena of Four Wave Mixing, Fiber Bragg Grating, Stimulated Raman Scattering, Optical Carrier Suppression and Stimulated Brillouin Scattering and few other terminologies which are used in this report.

2.1 Laser Source

The laser is a device which amplifies the light by phenomena of stimulated emission. The abbreviation of laser is light amplification by stimulated emission radiation (LASER). LASER was realized in 1954 and by 1960 the first laser light was developed in Hughes Research Laboratories. The laser is different from other light sources because laser ideally emits only single wavelength. However, practically the laser emits small range of wavelengths.

When a photon is incident on electron available at ground state, the electron moves to higher energy level by gaining energy by incident photon, this process in called absorption. After short interval of time typically in Nano seconds the electron come back to ground state by releasing photon (light) because excited state is non-equilibrium state. The direction of this photon is random and this process is called spontaneous emission. If a photon is incident on electron which is already available in excited state, then this electron come back to ground state by releasing two photons having same wavelength and same direction as shown in Fig. 2.1.

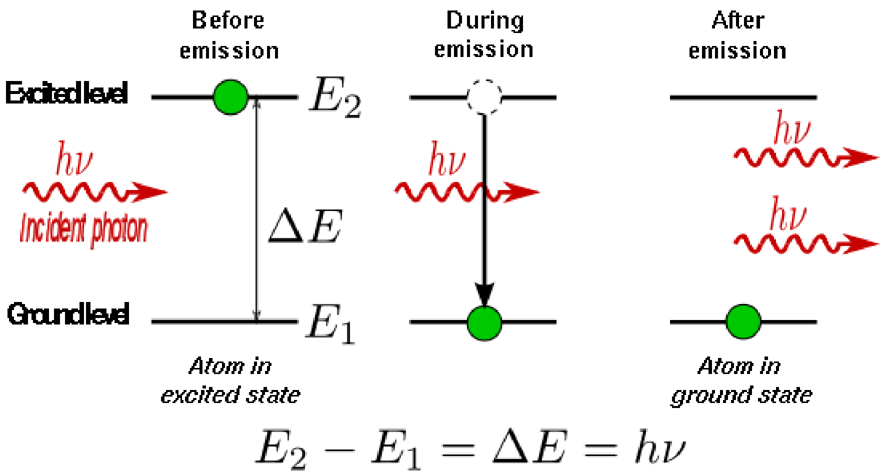


Figure 2.1: Stimulated Emmission [9].

A laser is based on a gain medium. The purpose of gain medium is to provide optical feedback and for energizing the electron to excited state. The wavelength passing through this gain medium will be amplified by the phenomena of stimulated emission. An external source which would be another light source or electric current is required for population inversion. This process is also called pumping. The external applied energy will be absorbed by atoms and electrons will be transferred to higher excited state.

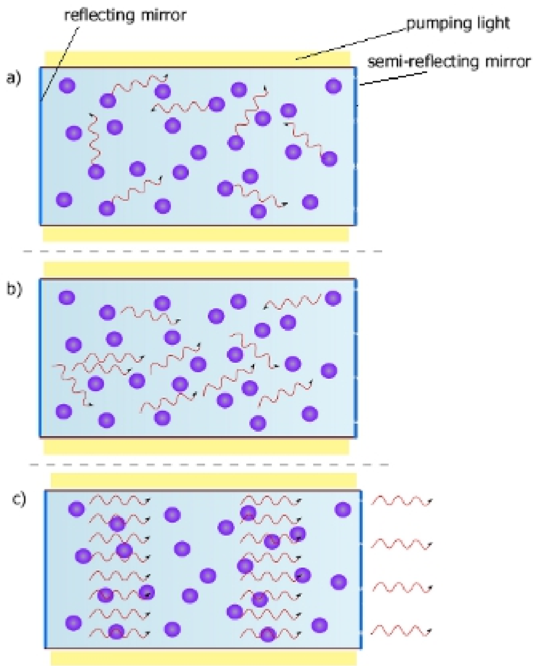


Figure 2.2: (a) Reflection of photons back and forth (b) Till gain saturation (c) Emission of laser light from semi-silvered mirror [10].

In most common lasers, there are two mirrors at both ends of gain medium. The light will be bounce back and forth between mirror and it will be amplified each time due to presence of excited electrons in gain medium. This amplified light will come out from one of the mirrors acting as a output coupler as shown in Fig 2.2. Depending upon the shape of mirror (curved or flat), a narrow or spread light will be emitted [9]- [10].

2.2 Mach Zehnder Modulator

The big amount of data is generated and transmitted in electrical domain. The data of multiple users are multiplexed in time domain before transmission over optical fiber at higher bit rates. The major functionality of optical system is to convert high data rates of electrical domain to optical one. This is called modulation. An ideal modulator should perform baseband to 193 THz frequency translation to use typical window of 1550 nm. So far the most famous approach is intensity modulation in which the intensity or power is varied according to order of data being transmitted. The data is recovered by photodetector which generate photocurrent according to variation of incident applied power. The phase and frequency modulation is also possible in optical communication.

There are two type of modulation, **direct modulation** and **external modulation**. In **direct modulation**, light is emitted only when “1” is transmitted and in case of “0” no light is transmitted as shown is Fig 2.3 (a). The direct modulation is simple and low complex method of converting electrical signal into optical one but the linear region is limited to electrical signal having frequency lower then 1 Gbps because change in modulating signal will result is change in refractive index leading to change of center frequency. This change in center of frequency is often called chirp. In **external modulation**, constant power is applied to continuous laser and the laser will emit constant light. Another component, a modulator is use to switch the light between “1” and “0” as shown in Fig 2.3 (b). The modulator should be fast enough to meet the higher requirement of data-rate conversion into optical domain. E.g. if the 10 Gbps data is required to be converted then the modulator should be fast enough to toggle between two states within 100ps window.

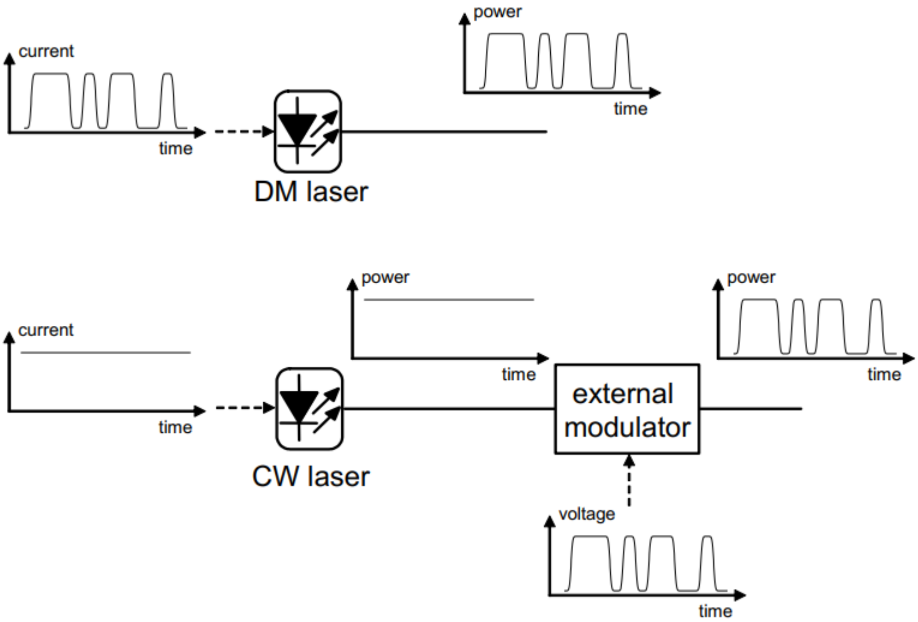


Figure 2.3: (a) Direct Modulation (b) External Modulation [12].

There are two types of optical modulators,

2.2.1 Electro-absorption Modulator (EAM)

The Electro-absorption modulator (EAM) is based on change of absorption of semiconductor material to applied electric field. The electric field decrease the bandgap E˙g. The decrease in effective bandgap will result is absorption of light wave by material. By properly choosing the wavelength, (as different wavelengths experience different fiber losses) optical intensity modulation

can be achieved by varying electrical voltage.
The Electro-absorption modulator (EAM) operates at low voltages. Due to change in refractive index, frequency chirping will be introduce, however this chirp will be lower then direct modulation.

2.2.2 Electro-optic Modulator (EOM)

The linear electro-optic effect can be used to vary the refractive index by applying electric field. The phase shift induced in a wavelength traveling through a medium having refractive index n is given as,

$$\phi = \frac{2\pi}{\lambda} nL \tag{2.1}$$

If such medium is subjected to varying electric field through applied voltage, then refractive index can be varied. A change in refractive index will introduce phase shift. Typical optical communication system is based on intensity modulation. Hence the phase to optical modulation is achieved by using interferometer structure.

In Fig 2.4, the principle of interferometer is shown. This structure is based on Mach Zehnder Interferometer in which one the arms of modulator contain electro-optic material typically lithium-niobate (LiNbO˙3). Assuming splitting ratio is 1/2 both at input and output couplers. The output power is dependent on phase difference between upper and lower arms as,

$$P_{out} = P_{in} cos^2 \frac{\triangle\ \phi}{2} \tag{2.2}$$

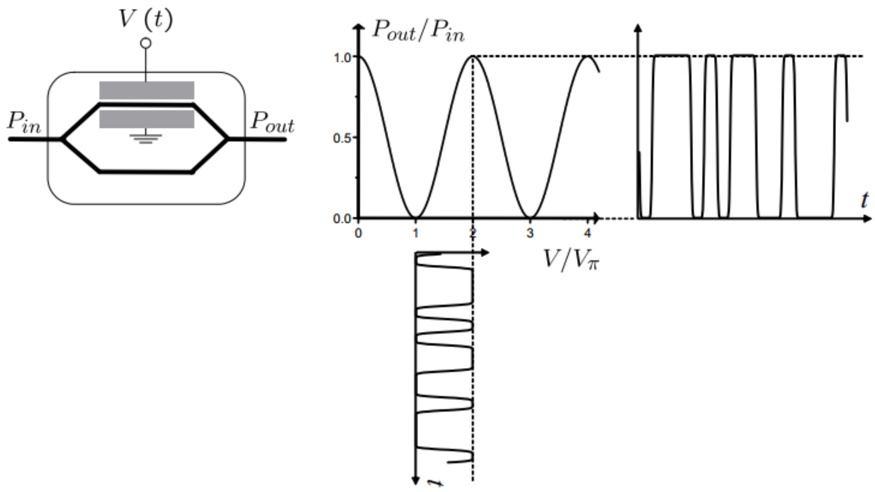


Figure 2.4: Principle of operation of Mach Zehnder Modulator [12].

The phase shift in upper arms is generated due to change in refractive index. Where refractive index is dependent on applied electrical voltage via electro-optic effect. If continuous laser is applied at modulators input then the output power will be modulated according to applied voltage $V(t)$. A lot of factors depends on the amount of phase shift. i.e. material, polarization and orientation of crystal and dimensions of waveguide. A phase shift of 180 degree is achieved between both arms if applied voltage is normalized to half wave voltage V_π as shown in Fig 2.4. Now the phase shift can be shown as,

$$\phi(t) = \pi \frac{V(t)}{V_\pi} \tag{2.3}$$

This method can also face the problem of frequency chirp. This problem is mitigated by applying complementary voltage at both arms. Modulator driving in this mode is called Push-Pull mode. Further detail is coming in $Section 2.10$ [11]- [12].

2.3 Optical Amplifier

The light inside optical fiber got attenuated due to various reason such as passive components like fiber coupler, multiplexer and de-multiplexers and splitters etc. In early 1980s the light was converted into electrical domain to amplify the signal and then light was converted again in optical domain to launched in optical fiber. This process increases the complexity and power losses.

One of the famous optical amplifier is Erbium-Doped Fiber Amplifier. This Amplifier was introduce in 1987 and EDFA amplify the signal without converting into electrical domain.

2.3.1 Erbium-Doped Fiber Amplifier (EDFA)

Erbium-Doped Fiber Amplifier (EDFA) is one of the amplifiers which is widely used in long distance optical fiber communication. It amplifies the light signal inside optical fiber and doesn't requires optical-to-electrical and electrical-to-optical conversion.

EDFA can be used as inline, booster or preamplifier in optical communication as shown in Fig. 2.5. the **booster amplifier** is placed after the transmitter to increase the intensity of light signal while the **inline amplifier** is place in the middle of transmission line to compensate against the attenuation occurs along optical fiber. The **pre-amplifier** is place before the optical receiver to enable receiver effective reception.

EDFA is nothing but a small piece of fiber (typical tens of meters) in which rare earth material erbium ions are doped in the glass of fiber to

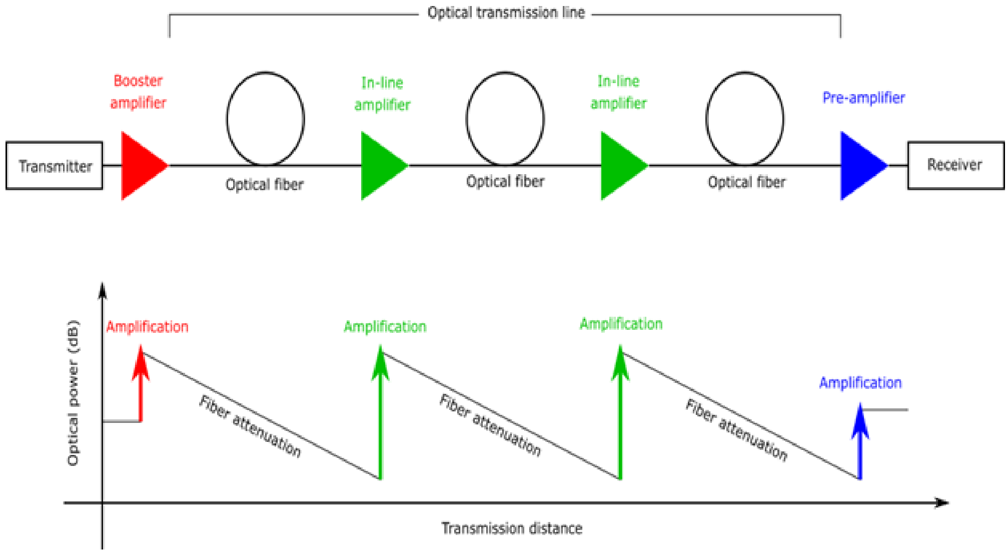


Figure 2.5: Placement of Booster, In-line and Pre-Amplifer [13].

enable absorption of certain pump frequency and amplification at another frequency.

The common bands used for pumping is 980 nm and 1480 nm. Both have slight difference in absorption rate. The 980 nm has narrow but higher absorption rate along cross-section, while 1480 has lower but broaden absorption cross-section. It is common to have both combinations in amplifiers. The signal exite erbium ions to the excited state 1 and 2 according to the choice of pump wavelength as shown in Fig 2.6. The excited state is un-stable state so the erbium ions after short interval come back to excited state 1 which is meta stable state and here the erbium ions stays for long time. When the wavelength around 1550 nm is launched into this piece of fiber and interreacts with erbium ions in excited state an amplification occurs based on stimulated emission. The erbium ions give energy to incoming light signal and go back to ground. This process continues, and light is amplified along

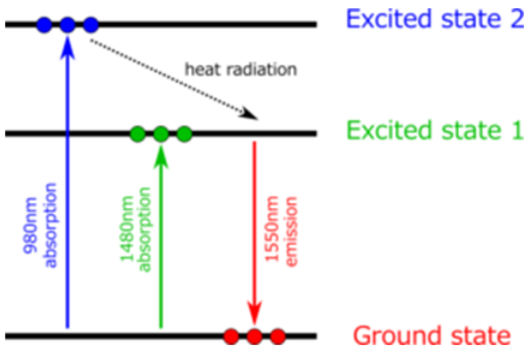


Figure 2.6: Energy Diagram [13].

optical fiber. [13].

2.4 Optical Fiber

An Optical fiber is a transparent, flexible fiber which is made up of silica (glass) or plastic with a very narrow diameter. Optical fibers are used to transmit data from one side of fiber to other end by mean of light. Optical fibers are light is weight and offer long distance communication with attenuation as low as 0.2 dB/km, offer high data rate (up to 100GHz) and they are immune to electromagnetic interference. These are limitations in traditional electrical wires.

Optical fibers contain core and transparent cladding. The core is surrounded by cladding. The index of refraction of core is lower then cladding. The light traveling inside the core and obeys the phenomena of total internal reflection. The optical fiber can be a **single mode** and **multimode**. **Single mode fiber** is used in relatively long distance communication while **multimode fiber** containing multiple optical signals have large core diameter and they are used in short distance communication having multiple channels. The important parameters of optical fiber acting as a delay lines are Fiber Losses and Dispersion.

Fiber losses are dependent on two main factors ,i.e, **material absorption** and **Rayleigh scattering**. The **material absorption** further sub divided into **intrinsic** and **extrinsic absorption**. The **extrinsic absorption** is the result of impurities in optical fiber while **intrinsic** impurity electronic and vibrational resonance in wavelengths of ultraviolent and infrared respectively. The extrinsic absorption (OH Absorption) includes water vapors in fiber which occurred during fabrication.

The **Rayleigh scattering** occurs due to minor variation in the refractive index of optical fiber and small amount of light reflects due to these variations. Unequal density of silica leads to Rayleigh scattering. Keeping above constraints the band with lowest loss is 1.5-1.6 μm.

The **dispersion** in the optical fiber is the phenomena of traveling of wavelengths with different speeds. This is because the wavelength are dependent on refractive index. The continuous wave laser includes finite range of wavelengths instead of single wavelength and due to variations in refractive index different wavelength travels at different speeds.

There are three types of fiber dispersion, modal, material and waveguide dispersion. The **modal dispersion** occurs in multimode fiber as group velocities of each mode is different from other. The **material dispersion** occurs in both single mode and multimode fibers. The reason of dispersion is change in refractive index due to change in wavelength. The waveguide dispersion occurs because the speed of a mode depends on power ratio traveling in core and cladding. The dispersion compensation fiber can be used to eliminate the effects of dispersion in optical fiber [14].

2.5 Photodetector

The Photodetector is an optical device which is used to convert light signal in to electric current. They are made up of semiconductor materials. When incident light hits the photodetector, the electrons of the semiconductor material absorb the energy from photons. This enables them to move towards conduction band from valance band. The moving electron leave hole and hence a pair of electron and hole is generated. In the presence of external applied voltage, the charges will flow and results in electric current which is referred to as photocurrent. A simple photodetector is based on reverse biased p-n junction. Hence the flow is opposite due to applied external voltage. The amount of current flows in circuits is dependent on the width of p-n junction. The main parameters of photodetector are Quantum Efficiency, Responsivity and Bandwidth. The **responsivity** of photodetector is ratio between generated current I_p and incident optical power P_{in}.

$$R = \frac{I_p}{P_{in}} \tag{2.4}$$

The **Quantum Efficeny** is the measurement of the photodetector's ability to convert light in electric current. It is ratio of electron generation rate to incident photon's rate. Rate of electron generation is the flow of current to the total charge q. While rate of photon incidence is total incident power to the energy absorb by the electrons in valance band of semiconductor material. Mathematically it is given by,

$$\eta = \frac{\frac{I_p}{q}}{\frac{P_{in}}{hf}} = \frac{hf}{q} R \tag{2.5}$$

Where h is plank's constant, q is electron charge and f is the frequency of photons.

The **bandwidth** of photodetector is basically is response against incident photons. It depends on rise time T_r which is the time a current takes to rise from 10 to 90 percent. This rise time is dependent on transient time which is the time needed for and electron to reached at the other end of photodetector and RC time constant of photodetector. The capacitance in RC time constant is dependent on the length of depletion region L_d. The rise time can be expressed as,

$$T_r = (ln9)(T_{tr} + T_{RC}) \tag{2.6}$$

It is desirable to have low transient time and this can be achieved by reducing the depletion length, however reducing depletion length reduce the area and hence the rate of electron generation. Reduction in electron generation will effect the efficiency and responsivity of photodetector. Hence there is tradeoff between responsivity of photodetector and bandwidth.

The most famous photodetector is Positive-Intrinsic-Negative (PIN) photodetector which contain lightly doped region between n-type and p-type. The PIN operates in reverse bias with high resistance in intrinsic region i as there is no free charges. The intrinsic region is kept larger to increase the

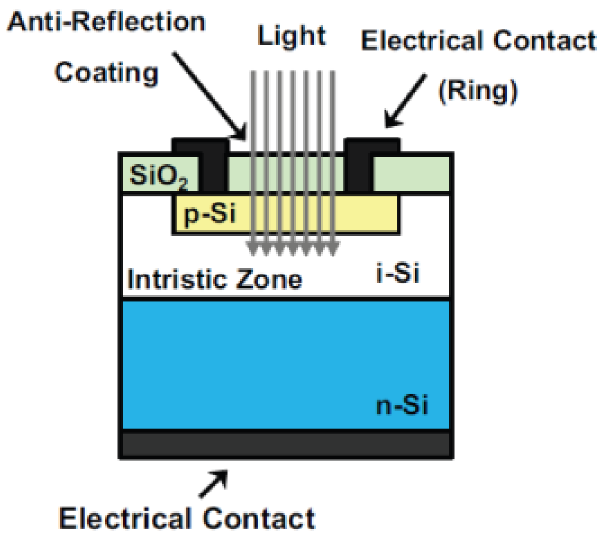


Figure 2.7: PIN Photodetector [15].

probability of incident photons to fall on this region as shown in Fig 2.7.

In reserve biased PIN photodetector, the photodetector doesn't conduct (only small dark current which is also called leakage current). When a photon of energy equal to difference between the two energy levels (valance to conduction band) hits the depletion region of photodetector then an electron-hole pair will be generated. Due to presence of external electric field the carriers sweep out of the region generating electric current [15].

2.6 Fiber Bragg Grating

Fiber Brag grating is type of reflector which reflects specific wavelength for which the phase-matching condition is satisfied and allow other wavelengths to pass through small segment of optical fiber without reflection. It is multi-layer structure having different value of refractive index and this causes reflection of desired wavelength.

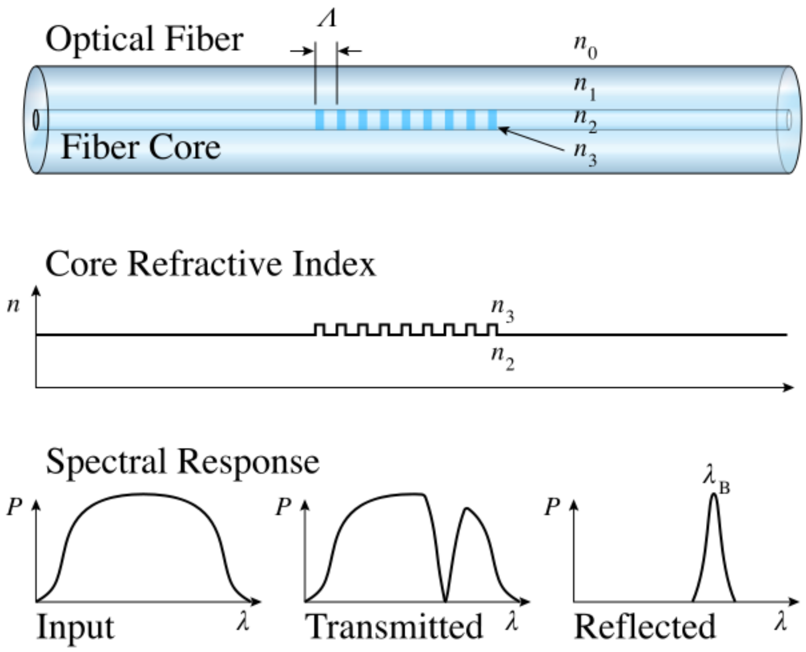


Figure 2.8: Strucure of Fiber Bragg Grating [16].

Normally this variation in core is periodic over length of fiber in centimeters or millimeters. Both incident and reflected wavelength travel across fiber axis in single mode fiber however the reflected wavelength travels in opposite direction as shown in Fig.2.8. The reflected wavelength satisfies the Bragg condition, which is given as,

$$\lambda = 2n_{eff}\wedge \tag{2.7}$$

where $\wedge$ is grating period, λ is the wavelength in vacuum, and n_{eff} is effective refractive index of light inside fiber [17].

2.7 Four Wave Mixing

Four-wave mixing is a nonlinear process which arises by third-order optical nonlinearity and is denoted by a $X(3)$ coefficient (Intensity dependent refractive index). It can take place when minimum of two distinct wavelengths propagate together with each other in a nonlinear medium like an optical fiber. Optical fiber can be made non-linear by reducing the effective area of fiber. When there are only two input wavelengths λ_1 and λ_2 in highly non-linear fiber with a condition.

$$\lambda_2 > \lambda_1 \tag{2.8}$$

The interaction of these two wavelengths in a time varying refractive index generates two additional wavelengths. The effect of incident light is increased inside fiber due to decrease in effective area. The increased incident light introduce variations in refractive index. The non-linear effects results in two newly wavelengths having relation with λ_1 and λ_2, as shown in Fig 2.9. Mathematical expression can be given as,

$$\lambda_3 = \lambda_1 - \langle \lambda_2 - \lambda_1 \rangle = 2\lambda_1 - \lambda_2 \tag{2.9}$$

and,

$$\lambda_4 = \lambda_2 + \langle \lambda_2 - \lambda_1 \rangle = 2\lambda_2 - \lambda_1 \tag{2.10}$$

The efficiency of four wave mixing depends on channel spacing (strong effects when wavelengths are closely spaced), chromatic dispersion, the power

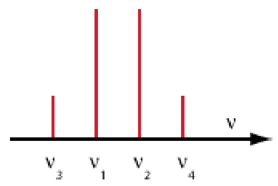


Figure 2.9: Four-Wave Mixing [18].

intensities of wavelengths involved, satisfaction of phase matching condition because four-wave mixing is phase-sensitive procedure (i.e. the interaction will depend upon the relative phases of all wavelength and it dosen't worked if there are greater phase mismatch conditions), length of fiber, refractive index and properties of higher order polarization of material (nonlinear Kerr co-efficient)

The impact of Four-Wave Mixing (FWM) can effectively build up over longer distance ranges and only if a phase-matching is satisfied [18].

2.8 Stimulated Raman Scattering

Stimulated Raman Scattering (SRS) is scattering of mono-chromatic light (single wavelength) which results in change in wavelength of light due to change in energy of light. This optical phenomena occurs when incident light interacts with some molecules of suitable transparent liquid or glass. The scattered light contain three possible type of energy level as shown in Fig. 2.10.

If all the incident light is converted into scattered light then this type

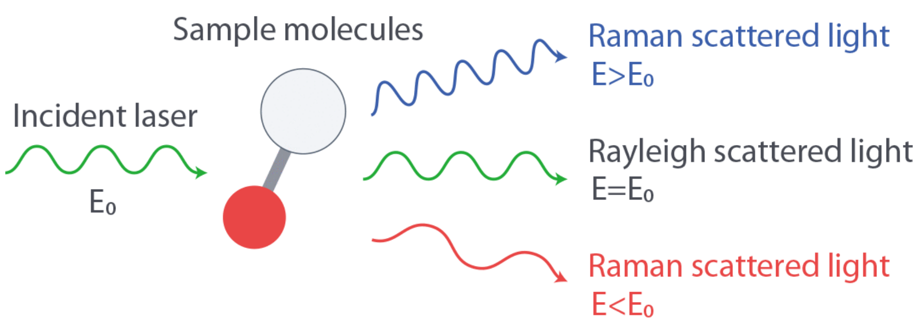


Figure 2.10: Scattering of light by molecules [19].

scattering is called **Raleigh Scattering**. In this case the electron is exited from ground level to exited level, as the exited virtual state is un-stable the electron immediately come back to ground state, resulting in scattering as shown in Fig 2.11 (a). The majority of the light is converted into Rayleigh scattering only the small fraction on light is converted into Raman scattering.

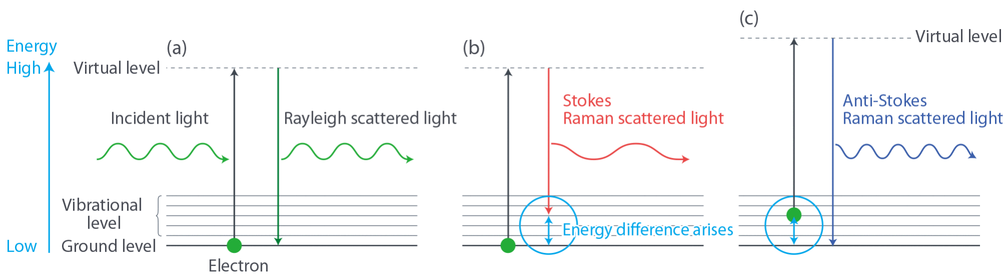


Figure 2.11: Stimulated Raman Scattring Process [19].

When the electron is excited from ground level and come back to higher vibrational level instead of ground level then scattered light has less energy (longer wavelength), this type of Raman scattering is called **Stokes Raman scattering** light as shown in Fig. 2.11 (b). In third scenario the electron in vibrational state is excited and this electron will come back to ground state, this light has higher energy (shorter wavelength) then incident light. This type of Raman scattering is called **Anti-Stoke Raman scattering** of light as shown in Fig. 2.11 (c). These vibrational frequencies are typically in infrared region hence a significant spectral shift can be achieved. [19].

2.9 Stimulated Brillouin Scattering

Brillouin scattering is an effect generated by third order nonlinearity $X(3)$ of a medium, particularly a nonlinearity that is associated with acoustic waves. Brillouin involves interaction of light with acoustic waves. Acoustic wave occurs between incident light and frequencies of material vibration. Hence a light scattered shifted from Brillouin scattering will be smaller amount from incident light.

The phenomena of electrostriction combine the optical fields and acoustic waves. Where **Electrostriction** is the property of dielectric and non-conductors materials to change their shape under the influence of electric field.

This process occurs spontaneously even with low optical intensities, however in case of high-power intensities the effect can be stimulated, which results in generation of more scattered lights. The stimulated Brillouin scattering reflect most of the incident light intensity at certain threshold power level inside medium. The process creates a powerful non-linear optical gain in backward direction which amplifies the suitable weak wavelength which is counter propagating in medium typical in range of 10-20 GHz range. These two counter-propagating optical waves creates traveling refractive index grating. This index grating will be high when higher optical intensity are reflected.

The difference between the frequency of incident and reflected optical wave is called Brillouin frequency shift and denoted as V_B. Brillouin shift can be calculated as,

$$V_B = 2nV_a \tag{2.11}$$

Where n is refractive index, V_a is acoustic velocity and λ is vacuum wavelength. This shift is dependent on the frequency of emitted photon, phase matching conditions, material composition and effect of temperature and pressure. The nonlinearity of silica is not high but nonlinear effect can be enhanced in small effective mode area and long propagation length. [20].

2.10 Dual Drive Mach Zehnder Modulator

As discussed in $Section 2.2$, Mach-Zehnder modulator are widely used in high speed digital optical communication system because it operates on large modulation bandwidth by biasing at low voltages and offer low chirp. There are two types of modulators used for amplitude and phase modulations ,i.e., single drive Mach Zehnder Modulator (MZM) and Dual Drive Mach Zehnder Modulator (DD-MZM). Among them dual drive $LiNbO_3$ is famous due to high compatibility with optical links. The modulated light wave entering in MZM is split into two paths having same length and both arms are connected to the external electrodes through which the phase can be varied based on electro-optic effect (Pockel effect). After introducing desired phase shift these two paths are recombined before output of modulator to produce constructive or destructive interference to achieved amplitude modulation. The electric field at DD-MZM is given as,

$$E_o = (\frac{E_1}{2}e^{(j\beta_1 L)} + \frac{E_1}{2}e^{(j\beta_2 L)})cos(\omega_c t)$$

$$= E_1 cos(\Delta\beta L)cos(\omega_c t)e^{(j\overline{\beta}L)} \quad (2.12)$$

Where,

$$\Delta\beta = \frac{(\beta_1 - \beta_2)}{2} \quad (2.13)$$

$$\overline{\beta} = \frac{(\beta_1 + \beta_2)}{2} \quad (2.14)$$

Where E_o is output electric field, E_1 is input electric filed, L is the length of arm, β_1 and β_2 are the propagation constants of paths one and two respectively. The cosine term in Eq. 12 is resultant amplitude modulation while the exponential function is time dependent phase variations, which is also referred to as chirp. By observing Eq. 2.13 and 2.14, it can be concluded that the problem of chirp can be completely compensated if the propagation constant in both arms are change by equal amount with opposite signs. DD-MZM with applied drive voltage of equal amount with opposite polarity at both electrodes can provide (theoretically) zero chirp modulator. [23]- [26]

The modulator is biased at different biasing points to achieve different type of modulations [21]- [22]. The modulator can be subjected to variation in desired bias point due to the thermal changes, photo refractive effects, aging effects and gathering of static electrical charges. These factors will results in horizontal displacement of modulator transfer function hence DC bias voltages ensures the locking of bias point at desired point to execute stable operation.

2.11 Optical Carrier Suppression (OCS)

The DD-MZM can be operated at null point to suppress the optical carrier as shown in Fig. 2.12,

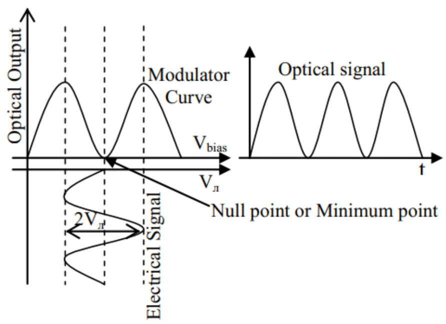


Figure 2.12: Transfer function of Mach-Zehnder Modulator.

The output of the modulator can be expressed mathematically as,

$$E_{out}(t) = E_o cos[\pi V(t)/2V_\pi] cos(\omega_c t) \tag{2.15}$$

Where ω_c and E_o are the frequency and amplitude of the optical carrier respectively. $V(t)$ is applied driving voltage and V_π is the half-wave voltage, a voltage which is required to introduce phase shift of 180^o between both arms. The driving voltage $V(t)$ includes amplitude of RF signal and DC bias voltage,

$$V(t) = V_{bias} + V_m cos(\omega_{RF} t) \quad (2.16)$$

Where V_m and ω_{RF} is the amplitude and frequency of RF signal respectively. V_{bias} voltage is differentially applied to the arms of modulator to bias the modulator at desired level. Now Eq. 2.15 can be re-written as,

$$E_{out}(t) = E_o cos(\pi/2[V_{bias}/V\pi + V_m/V_\pi cos(\omega_{RF} t)])cos(\omega_c t)$$

$$= E_o\{cosx.cos[mcos(\omega_{RF} t)] - sinx.sin[mcos(\omega_{RF} t)]\}cos(\omega_c t) \quad (2.17)$$

Where $x = (V_{bias}/2V\pi)\pi$ is the phase shift induced by V_{bias} , $m = (V_m/2V\pi)\pi$ is phase modulation index [23]- [26].

Eq. 2.17 can be expressed by using Bessel function. The output of DD-MZM using Bessel function can be expressed as,

$$E_{out}(t) = E_0 cosx\{J_o(m)cos(\omega_c t) + \sum_{n=1}^{\alpha}[J_{2n}(m)\cos(\omega_c t + 2n\omega_{RF} t - n\pi) +$$

$$J_{2n}(m)\cos(\omega_c t - 2n\omega_{RF} t + n\pi)]\}$$

$$+E_0 sinx\{[\sum_{n=1}^{\alpha}[J_{2n-1}(m)\cos(\omega_c t + (2n-1)\omega_{RF} t + n\pi +$$

$$J_{2n-1}(m)\cos(\omega_c t - (2n-1)\omega_{RF} t + n\pi)]\} \quad (2.18)$$

J_n represents the Bessel function of first order n. This expression comprises carrier component which is first term of the equation and the rest of both are odd and even side-bands respectively. If the bias voltage V_{bias} can be set to V_π to operate the modulator at null point, then $cos(x) = 0$ and $sin(x) = 1$ as $x = (V_{bias}/2\pi)\pi$. The output of modulator having suppressed carrier can be expressed as,

$$E_{out}(t) = E_0\{\sum_{n=1}^{\alpha}[J_{2n-1}(m)\cos(\omega_c t + (2n-1)\omega_{RF}t - n\pi)+ \\ J_{2n-1}(m)\cos(\omega_c t - (2n-1)\omega_{RF}t + n\pi)]\} \quad (2.19)$$

2.12 Polarization Maintaining Fiber (PMF)

A polarization maintaining fiber (PMF) is a type of single mode fiber (SMF) which maintains the state of polarization inside fiber during propagation with small or no-cross coupling of optical power. Such type of fibers are used for specific applications where maintaining the state of polarization is essential. The polarization state can be adjusted to change effective wavelength of PMF. The relation between wavelength spacing and effective length of PMF is given as,

$$\Delta\lambda = \frac{\lambda^2}{\Delta n}.L \quad (2.20)$$

Where Δn is birefringence of PMF and L is effective length. In ordinary single mode fiber (SMF) the polarization modes (i.e. vertical and horizontal) travel across the fiber with same phase velocity, however if there is bend or birefringence in fiber then even a small amount will result is large deviations in net polarization state. The **birefringence** is the property of optical material's refractive index dependent on polarization. However a linear birefringence is introduce in fiber to enable the fiber to maintain the state of polarization [27].

2.13 Polarization Differential Delay Line (PDDL)

Differential delay line is a device with split the light into two orthogonal polarization in side optical fiber. These orthogonal polarization modes are delayed w.r.t each other before recombining at output coupler to introduce tuning between wavelength spacing. There are various ways to introduce delays e.g. through control electronics [28]. The wavelengths spacing of the peaks is given as,

$$\Delta\lambda = \frac{\lambda^2}{c.\Delta t} \tag{2.21}$$

Where c is speed of light and Δt is the time delay which is introduce in orthogonal polarization.

Chapter 3

Literature Review

The Chapter 1 and 2 provides basic knowledge of microwave photonic filters and the basic devices used in optical communication. In this chapter we will discuss the research done in the field of microwave photonic filters in recent years.

3.1 Microwave Photonic Filter based on Four-Wave Mixing (FWM)

In *Section*2.7, the concept of four wave mixing is discussed. In paper [29], the microwave photonic filter is implemented using multi-wavelength optical source and delay line structure which is basically single mode fiber(SMF). The multiple wavelengths are generated via four wave mixing. In four wave mixing, two optical sources are pass through highly non-linear fiber. The single mode fiber (SMF) can be made non-linear by reducing the effective area of SMF. The will increase the power inside fiber and hence change in refractive index which leads to generation of additional side bands around actual two optical carriers subjected to phase matching conditions.

In this paper, two CW laser of wavelength 1559.6 nm and 1560.4 nm are used as a pump wavelengths. After the amplification by Erbium doped fiber amplifier (EDFA), these wavelengths are applied to higly non-linear fiber (HNLF) which has zero dispersion at 1562 nm. The dispersion slop of this fiber will be $0.018ps/nm^2$ with nonlinear co-efficient γ is equal to $10.8W^{-1}Km^{-1}$. The length of HNLF is 900 m. The output generates multiple wavelengths. The block diagram is shown in Fig. 3.1.

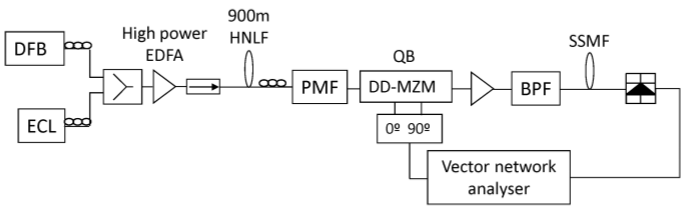


Figure 3.1: Four Wave Mixing (FWM) based MPF [29].

The number of wavelengths can be controlled by applying optical filter at output of HNLF. The power of EDFA can also be adjusted to control number of wavelengths. In this paper microwave photonic filter is implemented by utilizing 2 to 5 taps. The multiple wavelengths are modulated with RF signal to be filtered. The filter sample are realized by applying RF modulated optical signal to 25 km single mode fiber (SMF). Desired sampling time can be achieved by varying adjacent wavelengths or by varying length of dispersive fiber (i.e. Eq. 1.16). The vector network analyzer is used to analyze the filter response.

In paper [30], same approach is used and the tuning range achieved in this paper is 6.914 GHz to 30.729 GHz. The tuning is achieved by varying the wavelength between adjacent wavelength or by changing the length of fiber, as stated in Eq 1.16. The block diagram of this paper is shown in Fig. 3.2.

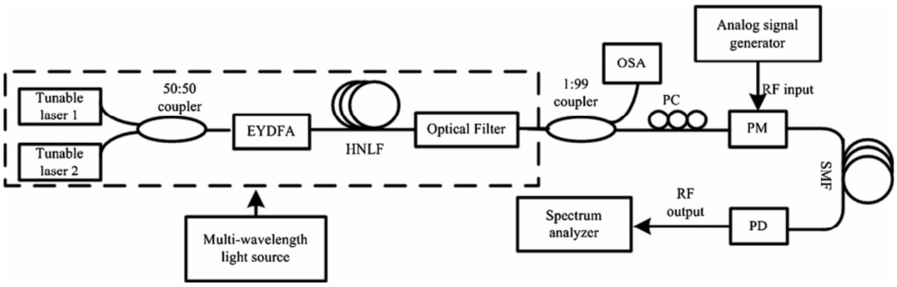


Figure 3.2: Four Wave Mixing (FWM) based MPF [30].

In this paper [31], the author has proposed the same implementation method by mean of four wave mixing (FWM) but with complex co-efficient. The multiple wavelengths generated by FWM are modulated with RF signal and applied to diffraction-based Fourier domain optical processor (FD-OP). FD-OP is programable device (Finisar Wave-shaper 4000s having 1 GHz resolution) which is used to adjust the amplitude and phase of optical carrier and upper sideband while eliminating lower side band which is 180 degree out of phase with upper side band because of phase modulation. By this mean the complex co-efficient are generated. The FD-OP will enable band pass to notch filter switching. The bandpass filter proposed in this paper have a tuning range from 5.853 GHz to 29.311 GHz [32]. The block diagram is shown in Fig. 3.3.

Figure 3.3: Four Wave Mixing (FWM) based MPF [31].

3.2 Microwave Photonic Filter based on Stimulated Brillouin Scatting

In this paper [33], the author proposed microwave photonic filter based on Brillouin erbium fiber laser(BEFL). The phenomena of Stimulated Brillouin Scattering is discussed in detail in *Section*2.9. The multiple wavelengths are realized by utilizing the gain of Brillouin and linear gain of Erbium Doped Fiber Amplifier (EDFA) as shown in Fig. 3.4. A Brillouin stoke wavelength with 10 GHz downward is generated by increasing the power from lower threshold of Brillouin gain inside fiber. The newly generated wavelength will be amplified to enable this stoke wavelength to generate another stokes wavelength. Hence this cascaded effect can generates multiple wavelengths. The number of wavelengths can be controlled by controlling the pump power which is used to control the gain of erbium doped fiber. The wavelength difference is small (i.e. 10 GHz)but Brillouin gain medium can be changed to get different wavelengths spacing and hence tunability can be achieved.
A BEFL of 5 km and EDF (205mW)of 10 m is used between mirrors. A 980 nm laser is used as a pump power for Erbium doped fiber (EDF). A Brillouin pump (BP) of wavelength 1558.4 nm is coupled to the laser cavity via 3 db coupler. The EDF pump power is responsible for generating

number of wavelengths while BP control the output wavelengths. At output a programmable spectral processor (PSP) is applied to modify the spectral profile. In this paper 8-taps are generated and they are modulated with RF signal to be filter out and processed in dispersive compensation optical fiber which act as a delay line. The RF signal is filter out at photodetector. The spectral response of filter is analyzed with networks analyzer. The tuning of free spectral range (FSR) is also achieved by controlling the Brillouin gain medium to change the wavelength separation. This is additional feature and add flexibility to the filter against conventional way to tune the spectral response by changing length of dispersive fiber.

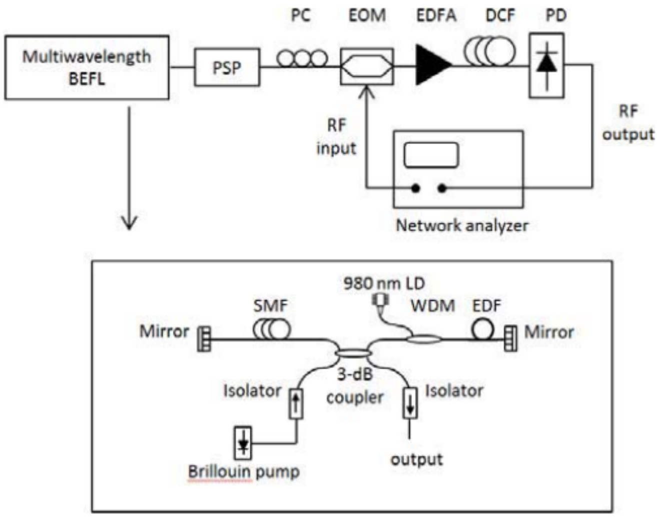


Figure 3.4: Stimulated Brillouin (SBS) based MPF [33].

3.3 Microwave Photonic Filter based on Sagnac Loop

In this paper [34], author proposed continuously tunable microwave photonic filter. The multiwavelength in loop is introduced into another loop which is based on polarization differential delay line (PDDL). The wavelength spacing between multiple wavelengths is achieved by controlling the PDDL. This multiwavelength laser is coupled again in main loop and amplified by semi-conductor optical amplifier(SOA). In this paper the wavelength spacing between multiple wavelengths is tuned from 1.2 to 6.8 nm. This multiwavelength optical source is modulated with RF signal to be filter out and processed in dispersive optical fiber which act as a delay line configuration. Multiple copies of composite are applied at photodetector to filter out RF signal. The tuning range of FSR is 1.84 to 0.33 GHz. The block diagram is shown Fig. 3.5.

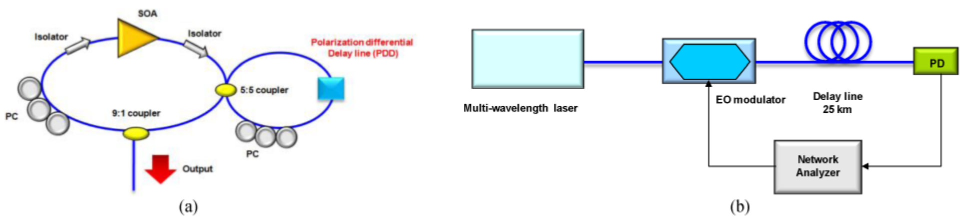


Figure 3.5: Sangnac Loop based MPF [34].

3.4 Microwave Photonic Filter based on Multi-Wavelength Fiber Laser and Infinite Impulse Response (IIR)

In this paper [35], multi-wavelength fiber is used along with dispersive fiber as a delay line. As discussed earlier, based on number of samples, the filter can be FIR or IIR. The IIR configuration can be realized using FIR configuration by introducing feedback loop from photodetector to dual drive mach-zehnder modulator (DD-MZM). The microwave photonic filter is based on ring cavity. The block diagram is shown Fig. 3.6.

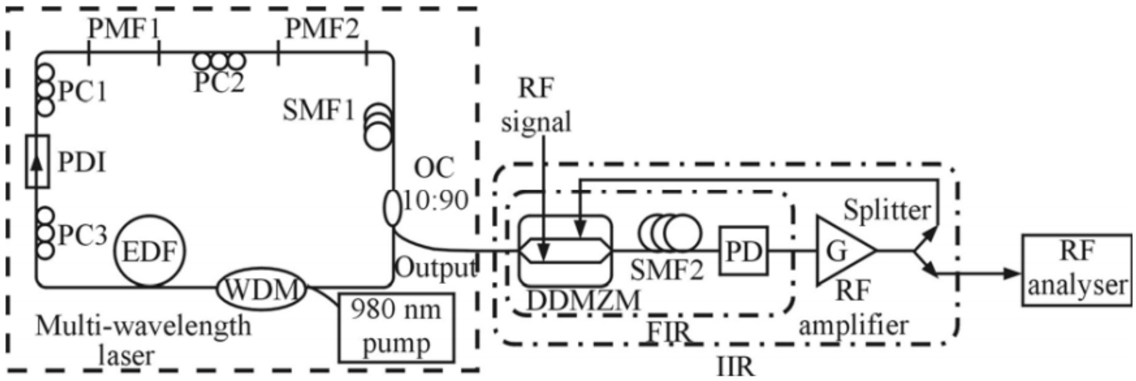


Figure 3.6: MPF based on IIR Configuration [35].

The ring cavity is based on Erbium doped fiber (EDF) of length 4m, pump power at wavelength 980 nm to generate multiple wavelength lasing, wavelength division multiplexer (WDM), polarization dependent isolator (PDI), to keep the transmission uni-directional, a singe mode fiber (SMF), three polarization controller (PC) and two section of polarization maintaining fiber

(PMF) of length 4 and 10 m. A 10:90 coupler is used to get output lasing wavelengths. As mentioned in *Section*2.12, polarization controller (PC) are adjusted to change the effective length of PMF which results in different wavelengths spacing. The relation between wavelength spacing and effective length of PMF is given as,

$$\Delta\lambda = \frac{\lambda^2}{\Delta n}.L \tag{3.1}$$

Where Δn is birefringence of PMF. 8-taps are realized with three different wavelengths spacing of 0.44, 0.78 and 1.08 nm and equivalently a tuning of FSR at 8.46, 4.66 and 3.44 GHz. These multiple wavelengths are applied at (DD-MZM) to convert into optical domain. A 15 km single mode fiber (SMF) is used as a dispersive medium. The RF signal is filtered out at photodetector. The same output RF signal is applied again at the input of modulator. Results shows that the FSR of FIR and IIR are same. However the Infinite impulse response (IIR) configuration is used to improve the effectiveness.

3.5 Microwave Photonic Notch Filter based on Stimulated Raman Scattering

In this paper [36], tunable multiple wavelength generation using multi-wavelength fiber laser based on Raman fiber gain. The wavelength spacing can be made tunable by setting Mach-zehnder interferometer (MZI) along with fiber laser. Controlling the Raman pumps and wavelengths spacing through MZI, the filter can be made tunable and re-configurable.The block diagram is shown Fig. 3.15, A 25 km of single mode fiber (SMF) is used as a Raman gain medium. Four

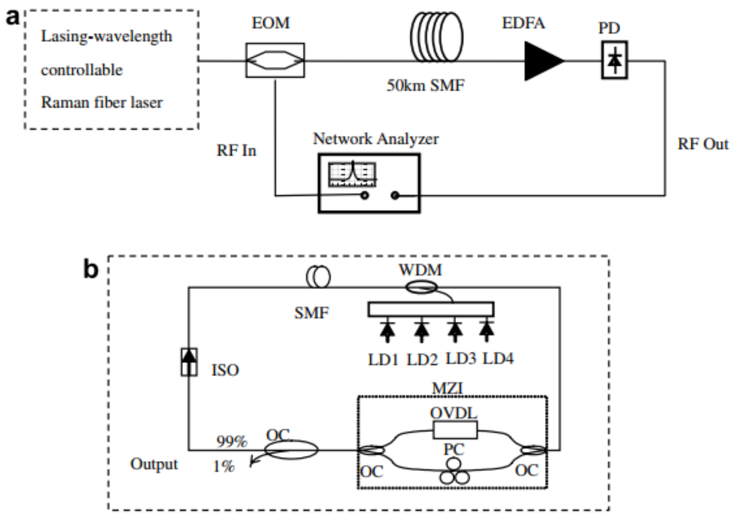


Figure 3.7: Stimulated Raman Scattering (SRS) based MPF [36].

Raman pump and MZI are set along SMF. The power of Raman pumps is adjusted such that to initiate Raman effect along 25 km SMF. The MZI is based on two arms and two 3-dB coupler at ends. One of th arms contain just PC while other include optical variable delay line (OVDL, MDL-002 General photonic corporation). The OVDL is controlled through computer. This OVDL provide 168 nm long range with low insertion loss and accuracy upto $3\mu m$. At utput of MZI, the delay different between both arms will results in change in wavelength separation. For instance the delay between wavelength can be varried from 0.1 nm to 100 nm by change length differentiate from 24 nm to 0.024 nm.

After the generation of multiple wavelength the multiple taps are modulated with RF signal to be filter out. The RF modulated optical samples are pass through another single mode fiber (SMF) which act as a dispersive fiber. The signal is filtered out at photodetector. In this paper three different wavelength spacing are realized i.e, 1 nm, 0.8 nm and 0.6 nm and equivalently range of FSR as 1.284 to 3.1 GHz.

Chapter 4

Proposed Design Methodology and Results

In chapter 1, 2 and 3 the basic understanding and techniques to implement microwave photonic filter are discussed. In this chapter the proposed method is discussed in detail.

In proposed scheme to generate multiple wavelengths, an RF signal is modulated with optical carrier by Dual-Drive Mach-Zehnder modulator (DD-MZM). The signal entering in modulator will be split into two paths and each path is connected to external electrode, where external voltage is applied to introduce a phase shift between these both similar signals. These signals will be re-combined at the output of modulator and difference in phase will be converted into intensity modulation.

The transfer function of MZM is non-linear (i.e.cosine function $Section 2.10$) hence higher order side-bands with frequency interval equal to applied microwave signal can be can be generated if DD-MZM is properly biased. The

DD-MZM is biased at null point to suppress the optical carriers which helps in doubling the interval between adjacent wavelengths. The variation in frequency interval between wavelengths can be achieved by varying value of microwave signal. This enables the tuning of filter's spectral response. The block diagram of proposed design is shown in Fig 4.1, The desired number of

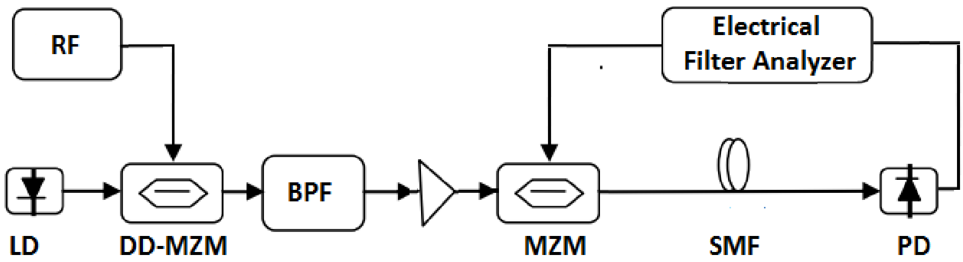


Figure 4.1: Block Diagram of Proposed Filter.

wavelengths are selected by passing through optical band-pass filter. These multiple wavelengths will act as a filter taps. After selection of multiple wavelengths, these wavelength are applied at Mach Zehnder modulator (MZM) for modulation with RF signal to be filtered.

The multiple wavelengths acts as a filter taps, hence a dispersive medium is required to introduce sampling delay. The single mode fiber (SMF) will act as a dispersive medium because of fiber dispersion each wavelength experience different delays. The cumulative sampling time delay T can be expressed as,

$$T = DL\Delta\lambda \tag{4.1}$$

Where D (ps/nm.km)is dispersive parameter of fiber, L is the length of dispersive fiber and $\Delta\lambda$ is the wavelength separation between adjacent wavelengths. For single mode fiber (SMF) the dispersion D is 17 ps/nm km. If fiber of length 10 km and wavelength separation $\Delta\lambda$= 0.735nm is selected then according to Eq. 4.1, the time delay will be equal to T = 125ps and FSR of 8GHz.

All the samples are applied at photodetector to recover RF signal. Since photodetector cannot response to high frequency of optical carrier hence the envelope of optical carrier is detected to recover RF signal.

4.1 Implementation of Proposed Model

The block diagram of proposed design is shown in Fig. 4.1. An RF signal of 25 GHz with amplitude 4v is generated and superimposed on CW light wave having wavelength of 1552.52 nm with power of 1mW (0dBm). In order to generate modulated output with suppressed carrier the DD-MZM is required to operate at null or minimum point. The DC bias values of $V_{dc_1} = 2v$ and $V_{dc_2} = -2v$ are applied at both arms to operate DD-MZM at null point. The default value of half wave voltage V_π is $4v$ and the values of DC bias voltages can be calculated from half-wave voltage V_π as the difference between DC bias voltages is equal to 4 for the case of operating DD-MZM at null point. Re-call Eq. 2.18 ($Section$2.11) the output electric filed from modulator using Bessel function can be expressed as,

$$E_{out}(t) = E_0 cosx\{J_o(m)cos(\omega_c t) + \sum_{n=1}^{\alpha}[J_{2n}(m)\cos(\omega_c t + 2n\omega_{RF}t - n\pi) +$$

$$J_{2n}(m)\cos(\omega_c t - 2n\omega_{RF}t + n\pi)]\}$$

$$+E_0 sinx\{[\sum_{n=1}^{\alpha}[J_{2n-1}(m)\cos(\omega_c t + (2n-1)\omega_{RF}t + n\pi +$$

$$J_{2n-1}(m)\cos(\omega_c t - (2n-1)\omega_{RF}t + n\pi)]\} \tag{4.2}$$

Where $x = (V_{bias}/2V\pi)\pi$ is the phase shift induced by V_{bias} , $m = (V_m/2V\pi)\pi$ is phase modulation index and J_n represents the Bessel function of first order n. This expression comprises carrier component which is first term of the equation and the rest of both are odd and even side-bands respectively. If the bias voltage V_{bias} (Where $V_{bias} = V_{dc_1}$-$V_{dc_2} = 2-(-2) = 4v$)can be set to V_π to operate the modulator at null point, then $cos(x)$ become zero and $sin(x)$ equal one as $x = \pi/2$. The output of modulator having suppressed carrier can be expressed as,

$$E_{out}(t) = E_0\{\sum_{n=1}^{\alpha}[J_{2n-1}(m)\cos(\omega_c t + (2n-1)\omega_{RF}t - n\pi) +$$
$$J_{2n-1}(m)\cos(\omega_c t - (2n-1)\omega_{RF}t + n\pi)]\} \tag{4.3}$$

These bias values are provided externally however these values can be selected within DD-MZM. The output of DD-MZM generates multi-wavelength optical source array which are equally spaced with a frequency interval equivalent to the double frequency of applied microwave signal due to optical carrier suppression is shown in Fig. 4.2.

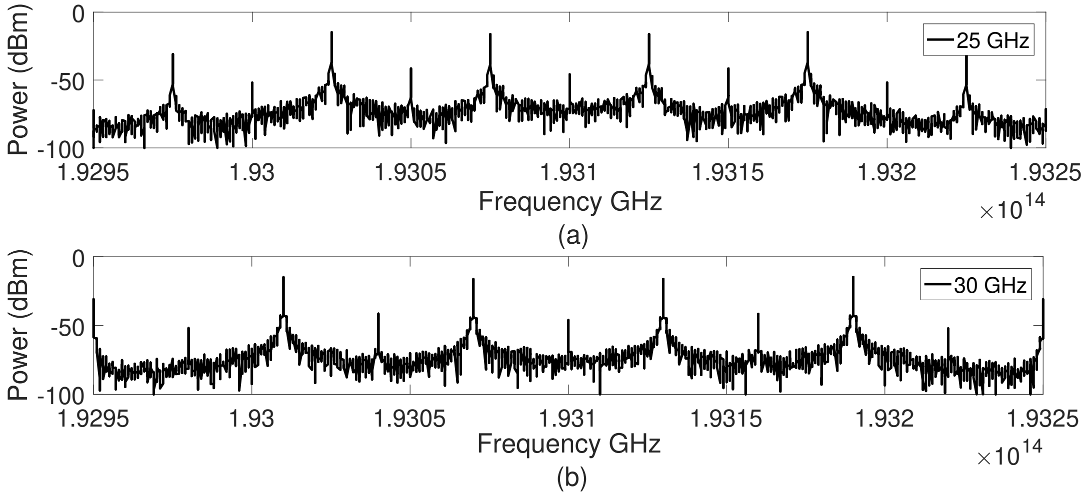


Figure 4.2: (a) RF Signal of 25 GHz (b) RF Signal of 30 GHz.

Fig. 4.2(a) and 4.2(b) shows the multi-wavelength source array having wavelength separation of 50 GHz and 60 GHz by using RF signal of 25 GHz and 30 GHz respectively.

The extinction ratio of modulator is the power distribution ratio between both arms. By default, the distribution between both arms is equal (i.e, 30 dB) however increasing the value of extinction ratio will further suppress the carrier. If the extinction ration is set 45 dB the optical carrier will be suppressed by 15 dB as shown in Fig 4.3. While the graph of extinction ration verses optical carrier suppression can be shown in Fig. 4.4.

After generation of multiple wavelengths, the optical bandpass filter (Gaussian) can be used to select desired number of filter taps. 3 and 4 taps are used in this configuration. The output of band-pass filter is amplified by using optical amplifier with a gain of 30 dB and noise figure of 4 dB.

These multi-wavelengths are modulated with RF signal to be filtered by

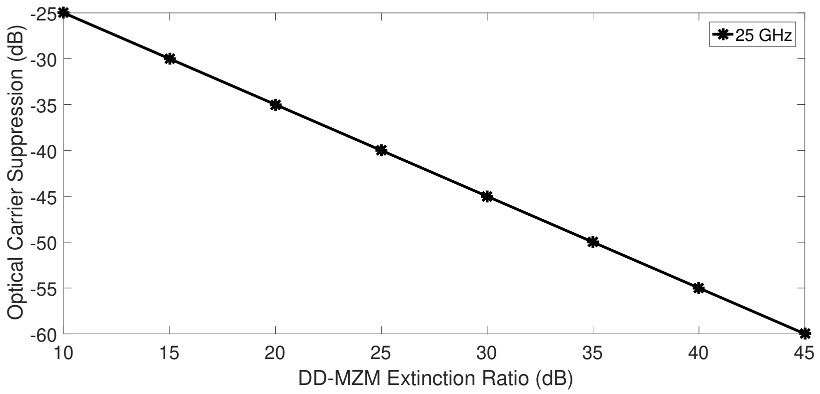


Figure 4.3: Optical Carrier is suppressed by 1 dB

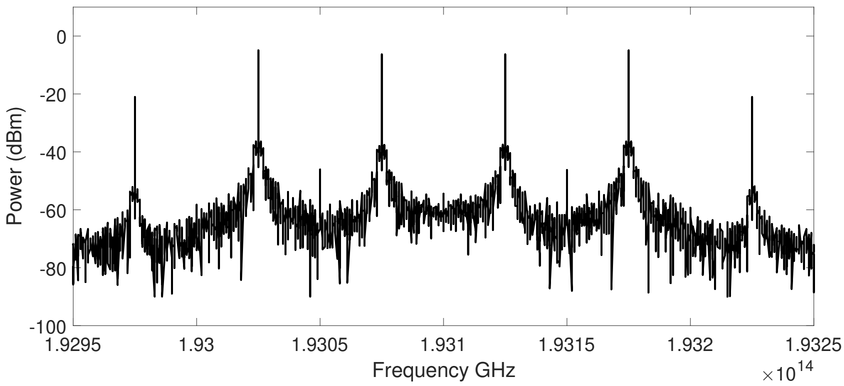


Figure 4.4: Optical Carrier is suppressed by 15 dB

single drive Mach Zehdner Modulator (MZM). To achieved desired sampling time T between the samples, these RF modulated optical carrier is applied to dispersive element which can be single mode fiber (SMF) of 30 Km. Re-call Eq. 1.16 ($Section$1.1) the total sampling time T can be expressed as,

$$T = DL\Delta\lambda \tag{4.4}$$

Where D (ps/nm km)is dispersive parameter of fiber, L is the length of dispersive fiber and $\Delta\lambda$ is the wavelength separation between adjacent wavelengths. The dispersion of SMF is 16.75$ps/nmkm$. The separation between wavelengths and length of optical fiber can be varied to different sampling time.

The impulse response for N-tap delay line microwave photonic filter with FIR configuration can be expressed as,

$$h(t) = \sum_{r=0}^{N-1} a_r \delta(t - rT) \tag{4.5}$$

The impulse response of 3 tap microwave photoic filter can be expressed as,

$$h(t) = \delta(t) + \delta(t - T) + \delta(t - 2T) \tag{4.6}$$

Converting into frequency domain will give us,

$$H(e^{j\omega}) = 1 + e^{-j\omega T} + e^{-2j\omega T}$$

$$= e^{-j\omega T}(1 + e^{j\omega T} + e^{-j\omega T})$$

$$= (1 + 2(cos(\omega T))e^{-j\omega T} \tag{4.7}$$

The magnitude and phase response from Eq. 4.7 can be concluded in Eq. 4.8 and 4.9 as,

$$|H(e^{j\omega})| = (1 + 2(cos(\omega T)) \tag{4.8}$$

$$\measuredangle H(e^{j\omega}) = e^{-j\omega T} \tag{4.9}$$

From Eq. 4.8 we can observe that the the filter is low pass, while Eq. 4.9 shows that the filter has a linear response. The responsivity of photodetector is set to $0.9A/W$. The electrical filter analyzer is used to analyze the transfer function of filter. The results using different values of fiber length and wavelength separation with 3 and 4 taps is shown in Fig. 4.5, 4.6 and 4.7 respectively. The upper and lower parts of these figures shows the filter con-

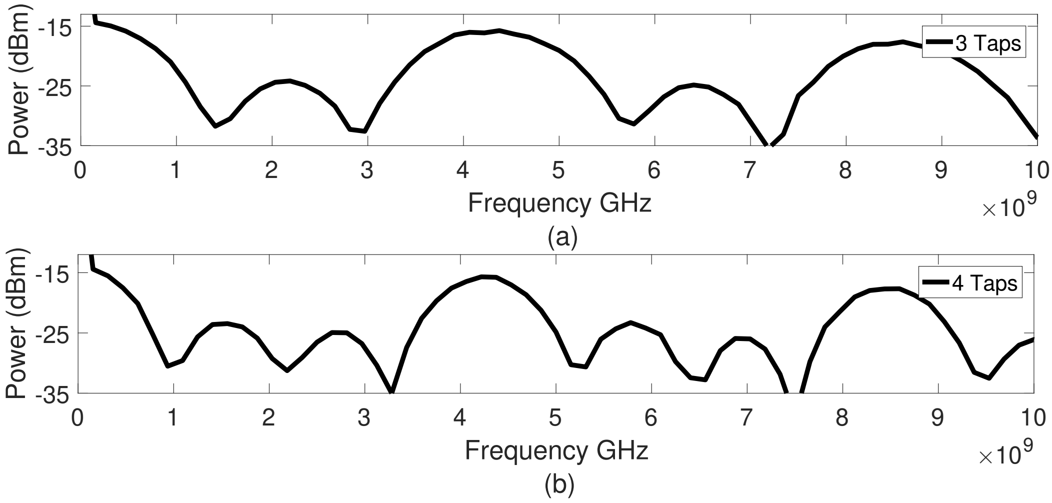


Figure 4.5: RF Signal = 25 GHz, Length of Fiber = 35 km Time Delay = 234.5 ps and FSR = 4.26 GHz.

figuration with 3 and 4 taps respectively. In Fig. 4.5, the length of fiber is 35 km and the wavelength separation between adjacent wavelength is $\Delta\lambda$=0.4, this results in time delay T of 234.5 ps and equivalently FSR of 4.26 GHz. The fiber length and wavelength separation can be varied to tune the filter response. In Fig. 4.6 the length is changed to 30 km while keeping other parameters same. This will result in time delay T of 201 ps and the FSR is tuned from 4.26GHz to 4.97GHz. In Fig. 4.7, the wavelength separation is changed to $\Delta\lambda$=0.48, now the total time delay T of 281.4ps is achieved and response is tuned from 4.97 to 3.55 GHz.

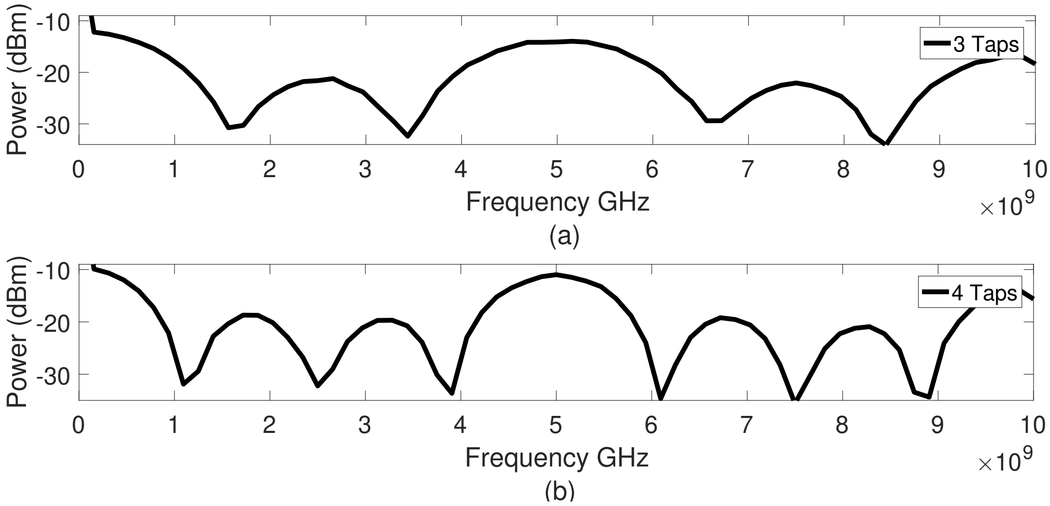


Figure 4.6: RF Signal = 25 GHz, Length of Fiber = 30 km Time Delay = 201 ps and FSR = 4.97 GHz.

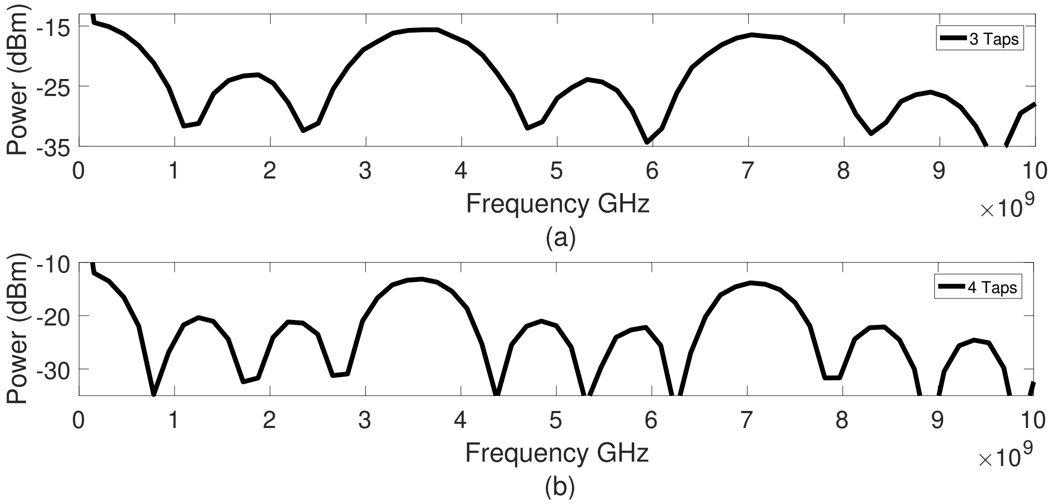


Figure 4.7: RF Signal = 30 GHz, Length of Fiber = 35 km Time Delay = 281.5 ps and FSR = 3.55 GHz.

Chapter 5

Conclusions And Future Work

5.1 Conclusion

Multitap microwave photonic filter is implemented by using novel technique based on single CW laser. The filter can be made tunable and reconfigurable by controlling the RF signal for wavelength generation, length of fiber and number of taps. Experimental results validates tunable microwave photonic filter using 3 and 4 taps by proposed scheme. This is simple and in-expensive approach to design an in-coherent microwave photonic filter with FIR configuration.

In Chapter No. 1, a comprehensive background of Microwave Photonic Filters and its applications are discussed. A microwave photonic filter based on finite impulse response (FIR) and infinite impulse response (IIR) using single and multiple source based microwave photonic filters are discussed.

In Chapter No. 2, basic devices used in optical fiber communication (i.e, Laser, Mach Zehnder Modulator, Optical Amplifier, Optical Fiber and

Photodetector), specially in microwave photonic filters are discussed. This chapter also discussed the concept of fiber bragg gratting, four wave mixing, stimulated Raman scattering, stimulated Brillouin scattering, dual drive mach zehnder modulator and optical carrier suppression technique are discussed.

In Chapter No. 3, the literature review on latest microwave photonic filtering based on multiple wavelengths is covered. Major microwave photonic filters are based on Four Wave Mixing (FWM), Fiber Bragg Grating (FBG), Stimulated Brillouin Scattering (SBS), Sangnac Loop and Stimulated Raman Scattering (SRS).

In Chapter No. 4, the proposed model of microwave photonic filter based on finite impulse response (FIR) in in-coherent regime is discussed and implemented using 3 and 4 taps. The multiple wavelengths are generated by using CW laser. The optical carrier suppression technique is also incorporated in this scheme.

5.2 Future Directions

We have implemented microwave photonic filter using FIR configuration in in-coherent regime. All the filter coefficients are positive and according to signal processing theory the filter with positive co-efficient have always resonance at base-band and hence operate as a low pass filter.

Different techniques have been proposed to generate negative coefficients to achieved band pass functionalities. For instance in this papers [37]- [38], positive and negative coefficients are generated by using electro-optic polarization modulator along with optical polarizer. The input light intensity is adjusted at 45 or 135 to the principle axis of modulator by adjusting polarizer. This will results in inverted and non-inverted optical modulated RF signal leading to positive and negative coefficients.

In an another technique multi-tap microwave photonic filter is implemented by using phase modulator and dispersive element. This approach is different from intensity modulator which the sidebands are in-phase instead of out of phase as the case in phase modulator. If RF modulated optical is applied directly at photo-detector then RF signal will not be recovered because the upper and lower band will cancel their effect. However if the RF modulated signal is pass through dispersive element then the phase different is partially or completely become in phase and the RF signal will be recovered at photo-detector. This combination of phase modulator and dispersive element will remove the problem of based-band resonance of low pass filter and it will be converted into band-pass filter [39]- [40].

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