

## Experimental Study for the Different Methods of Generating Millimeter Waves

Aamer Jamal Albaghdadi

department of electrical power, Instant Department, Telecommunication And Navigation Institute, The Public Authority for Applied Education and Training (PAAET), Kuwait ,

### Abstract

In this paper a analytical comparison and experimental implementation of different methods used in generating a low phase noise millimeter wave signals is presented. Four techniques were experimented and compared, Multiplication, phase lock loop (PLL), Injection locking (IL), and Injection locking with phase lock loop (ILPLL). The comparison and experimental results of a laboratory discussed.

**Keywords:** generating millimeter waves, Multiplication, phase lock loop (PLL), Injection locking with phase lock loop (ILPLL)

### I. Introduction

In this research, previous contributions in generating millimeter wave signals are reviewed tested, and compared. Optical millimeter wave signals techniques provide solutions to obtain high purity millimeter wave signals [1]. Not only that, but also extremely wide bandwidths are afforded by the characteristics of optical components beside the simplicity in configuration compared to electronic based techniques. An important advantage of transmitting millimeter wave signals over fiber systems is reducing the high attenuation occurred to the signals via the water molecules and oxygen in the atmosphere [2]. Radio over fiber systems allow frequency reuse and improve the security of communication systems. The availability of an optical source at the millimeter wave frequencies or higher, accepted stability level and phase noise, minimal requirement for using electrical signals, and having the largest independent devices are the main features in using the optical field in several applications [3],[4].

Optical fiber has immunity to interference and small size with light weight [5]. So far, the generation of millimeter wave signals with high frequencies is considered as a big challenge for conventional electronics [6]. Its importance is in providing high frequency waves in which wireless broadband applications and future cellular systems can rely on. Reliable, low cost components and technological principles are required to the successful future broadband mobile cellular communication systems. Many base stations are needed in pico-cell technology, so that radio over fiber is useful in transmitting and generating millimeter wave signals [6,7,8]. Another attractive problem to be solved is the distribution of millimeter wave signals sent from one central station to several remote antenna units lie in one area. For

example the distribution of 1000 remote antenna units over an area with radius 10 km [9]. Millimeter wave signals have an extreme attraction in biomedical engineering. Electromagnetic fields millimeter wave unthermal intensity is applied in treatment of a broad spectrum of diseases [10]. The disadvantages of applying photomixing based on photonic technologies are: the limitation of its size and the high cost compared to electronic systems [1].

### II. Modulating the Optical beam – External modulator:

In figure 1, millimeter wave signals with frequencies between 90 GHz and 125 GHz were demonstrated. The generated signals had low phase noise less than -75dBc/Hz at 100Hz offset. In the first setup, optical filters and optical couplers were connected through optical fibers. The measured signals showed phase fluctuations and high phase noise because of the change in length of the fiber path. The fluctuation problem and the phase errors can be solved by using injection locking methods or heterodyning the output of different slave lasers synchronized with the comb modes. These methods are discussed later [5],[12],[13]. The change happened due to the temperature and the phase difference between the two modes. To solve that problem, planer light-wave circuit PLC was implemented and added to the setup. That circuit consists of 3-dB combiners and AWG. Two modes were chosen from the generated comb frequency and coupled to the planer light-wave circuit. After integrating that circuit, the phase fluctuation was suppressed and the phase noise was decreased by 20dB. The used AWG had spacing frequency equals to 60 GHz and each channel had a 3dB bandwidth of 22GHz. The output was obtained from 120GHz separated channels. The temperature was an essential

point in this experiment to avoid the fluctuation of the optical path between the two modes. Changing the optical frequency generator can help in extending the method output to THz signal generation.

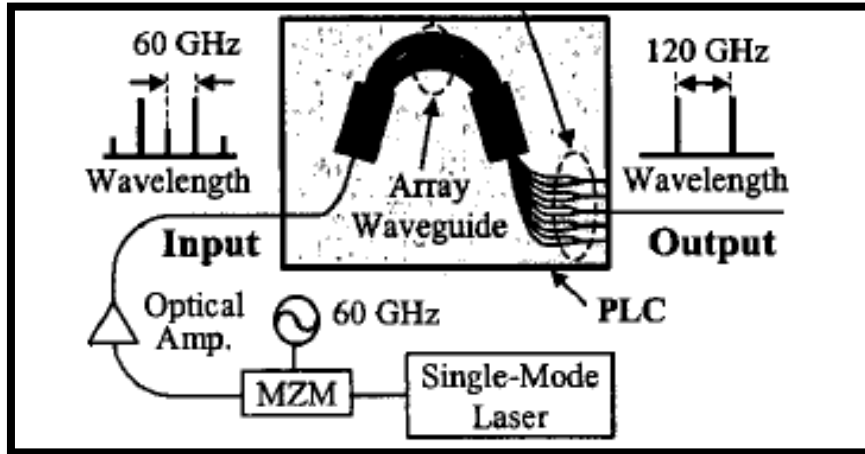


Figure 1: the experiment scheme.

An 1.4 Gbps PSK signal could generate with 22 GHz mm wave carrier. An optical beam was modulated by Mach Zehnder modulator, and then it was detected by optical homodyne technique. High speed photodetector for wireless transmission was utilized. After generating the comb lines, they could

modulate the millimeter wave signals with an ASK or PSK signal through an intensity modulator. Before applying the data modulating, the comb lines passed through FBG (Fiber Bragg Grating) to suppress the carrier component of the first modulator.

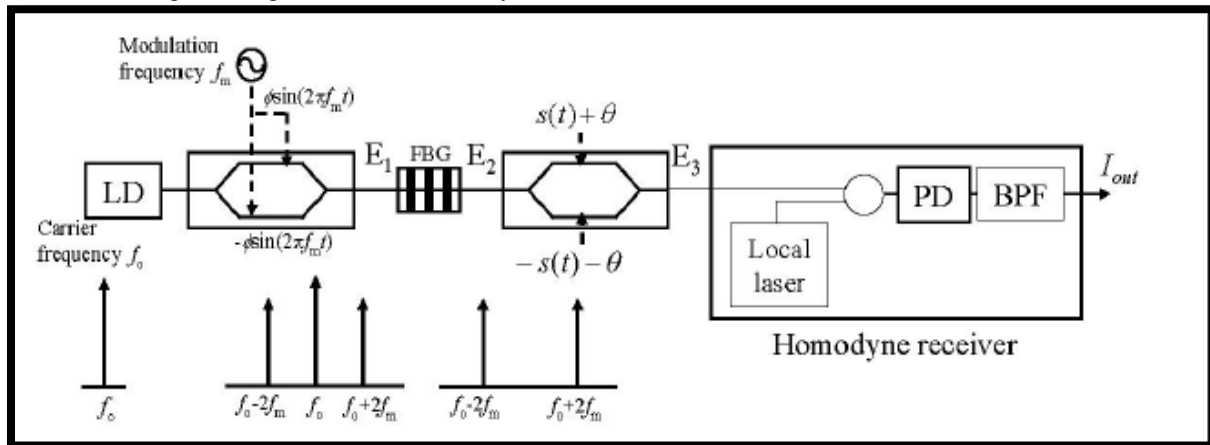


Figure 2: the experiment setup used and the optical fields are shown.

The optical millimeter wave obtained by the first modulator – in figure 2 - is:

$$E_2 \propto e^{j2\pi f_0 t} \cos(4\pi f_m t) \quad (1)$$

The optical millimeter wave obtained by the second modulator is:

$$E_3 \propto e^{j2\pi f_0 t} \cos(4\pi f_m t) \cos[s(t) + \theta] \quad (2)$$

The finally obtained electrical signal is:

$$I_{out} \propto \cos(4\pi f_m t) \cos[s(t) + \theta] \quad (3)$$

A novel technique for generating frequency quadrupling is presented in [15]. This technique gets rid of ultra-narrowband optical filter from the experiment scheme, which decreases system's stability and increases its cost. The new technique

depends on implement two cascaded Mach-Zehnder modulators separated by a tunable optical delay line in the experiment scheme. Adjusting the time delay between the two modulators is a key issue. The correct adjustment leads to the generation of two wavelengths spaced with a frequency equals four times the frequency used as a drive signal. After that, the pair of wavelengths passes through a third Mach Zehnder modulator that has intermediate frequency (IF) and used for upconversion. Then, the millimeter wave signal is obtained from the third MZ modulator output. That obtained signal can be distributed to remote stations through optical fibers. The received signals are then recovered by photodiodes. This technique can generate high frequency local

oscillator signal by using low frequency local oscillator signal. Not only that, but also it helps in generating signals with high tolerance to the dispersion induced power compared with other techniques. The schematic diagram of the experiment is shown in figure 3. A 33.125 GHz electrical signal was generated with 8.28125 GHz drive signal. In another experiment, two cascaded MZMs was

implemented too. A tunable electrical phase shifter was added to the experiment set up. The problem in the last method is the requirement to provide high frequency and the system was not pure optical. It was hybrid between electrical and optical signals not like the first technique which was pure optical system. Beside the high cost of the set up.

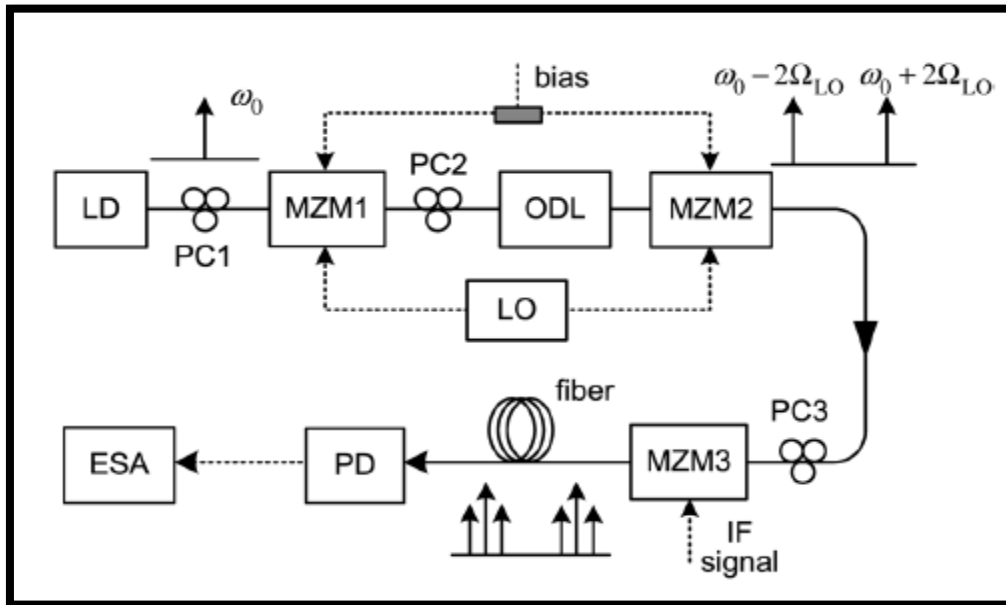


Figure 3: the schematic diagram with three MZ-modulators.

It was observed that transmitting single side band SSB in the radio over fiber field is dominant. Any double sideband signal suffers from the high chromatic dispersion loss level in fiber wireless systems. This dispersion could be overcome in [16] by using the dual-electrode MZ modulator to generate an optical signal with single side band modulation. The dual-electrode MZ modulator operates as a parallel two phase modulators. 51.8 Mb/s pseudorandom bit sequence was transmitted at 12 GHz over 80 km of single mode fiber. The main problems faced in the process of the previous method are the high insertion loss and the requirement for very large drive voltages at high frequencies. Mach-Zehnder modulator can be applied in optical systems to provide the modulation of the information signal or the data stream on generated millimeter wave signals.

### III. Direct Modulation and Self Pulsation:

The previous technique relies on modulating the optical output beam from the laser diode. Modulating the Electrical side instead of the optical side of a laser diode in an optical system helps in generating millimeter wave signals. This method is considered as the most straight forward approach. The generated signal properties depend on the device characteristics.

The maximum frequency reported was 40GHz [3],[14]. This technique is limited by the laser chirp and the lower frequency response [11].

A repetition rate equals to 40 GHz was achieved with overcoming the previous problems by implementing the direct mode locking on a monolithically integrated extended cavity laser – shown in figure 4-. This laser was fabricated in three MOCVD phases. One step for the base wafer when the others for the regrowths. Two main layers in the laser structure: a passive wave guiding layer and a thin active region. A semi-insulating blocking layer was added to provide current confinement to the active region. That layer helps in preventing the capacitance contact between the layers and in ensuring low propagation losses. In the test phase, two resonances frequency response were observed. The intrinsic relaxation oscillation frequency and the extended cavity resonance, at 2 GHz and 20 GHz, respectively. The first resonance frequency is low in the extended cavity laser because of large effective photon lifetime. That property is absent in conventional semiconductor lasers without an extended cavity. The mode locking was applied by using a hybrid integrated bias insertion circuit. A low phase noise synthesizer reference frequency signal derived the setup.

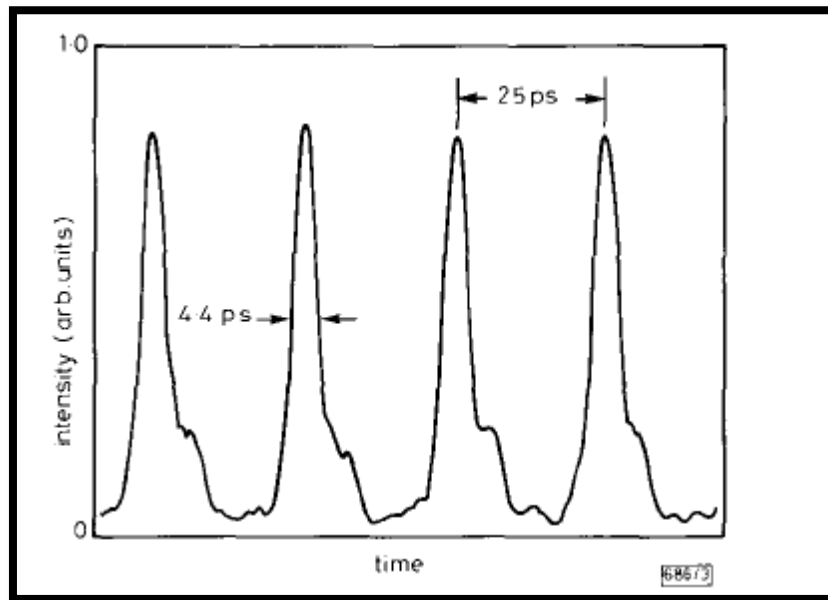


Figure 4: the measured pulses with 40 GHz repetition rate and 4.4 ps pulse width.

#### IV. Heterodyning techniques:

Another suggested method in generating millimeter wave signals is heterodyning two wavelengths [1]. A millimeter wave signal was generated by directly photomixing two lasers. Two discrete laser sources – that give continues wave optical signals- with different wave length were used. This experiment expects that the photomixing technique by two discrete laser sources can be helpful to characterize a wideband opto-electric component. The experiment set-up is shown in figure 5. The

frequency of the photomixed output is decided by the wavelength differences between the two tunable lasers. The photomixed output power is decreased by increasing the polarization angle difference. A dramatically reduction was observed around  $80^\circ$  of the polarization angle difference. The reason was the cancellation in the electric field of the two optical signal when the polarization angle difference reached  $90^\circ$ . For that, the polarization angles should be seriously controlled in the photomixing experiments.

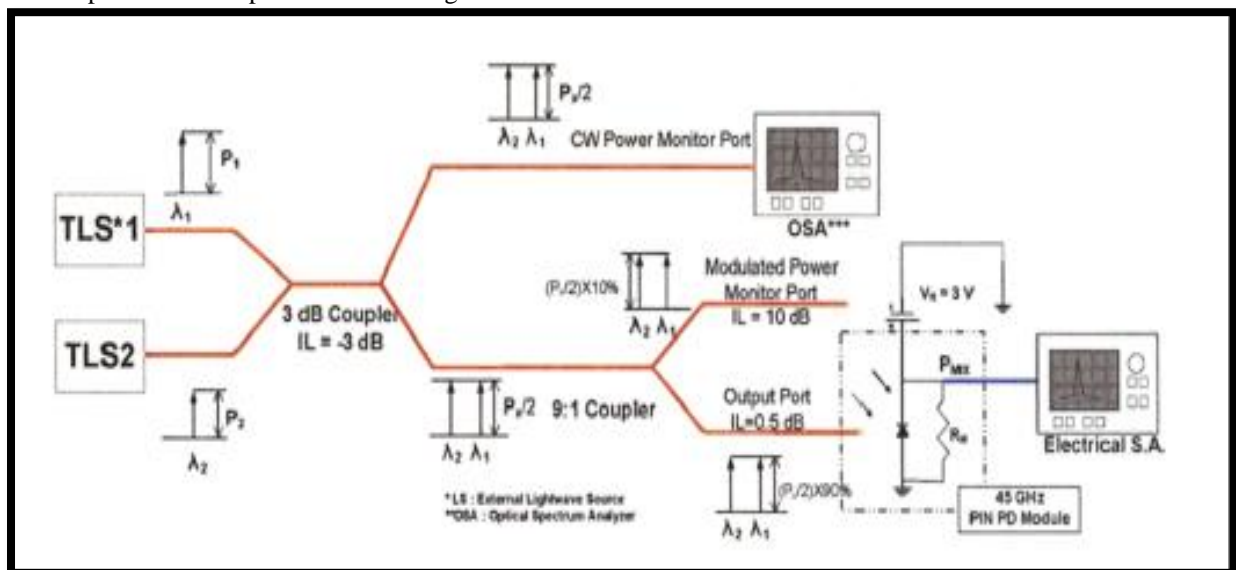


Figure 5: the set-up of the experiment.

From the problem faced in the setup of heterodyning two lasers experiments should be improved. Using a coupler and a photodetector at the output term is not sufficient in generating millimeter

wave signals. Large phase noise is an essential problem in generating millimeter wave signals, beside the difficulty in synchronization with external circuits in the operation scheme. These problems can

be solved by adding a stabilization phase to the scheme such as sub-harmonic optical or electrical injection techniques. The range of frequencies over which the generated signals frequency can be tuned from the cavity resonant frequency of the slave laser with the signal phase noise remaining within 1 dB of that at zero frequency detuning is defined as the locking range.

The locking range is larger than 400MHz. The maximum achievable millimeter wave frequency is limited by the references modulation performance of the master laser or the slave laser. In experiment, the short optical pulses are generated by using a single chip colliding pulse mode locked semiconductor laser instead of the regular laser PINs. The colliding pulse mode locked lasers benefit in generating millimeter wave signals in optoelectronic systems.

**4.1 Injection Locking (IL):**

Injection locking is a promising technique that has a simple configuration and an ability to produce pure and stable millimeter wave signals [8],[18],[20]. The lasers in such experiments work as optical narrow-band filters, as amplifiers and as phase modulators. 2GHz beat signal was generated by injecting a slave laser to FM sidebands of a master laser. The frequency response was flat and it was detected by a GaAs photodiode. The optical frequency of the slave lasers was controlled by varying their heat sink temperature an DC drive current. In [17], By using DFB lasers and choosing optical injection locking technique, the desired comb lines could be selected and isolated. In order to generate the frequency comb lines, the inserted signal from a reference frequency source underwent phase

modulation on each round trip. The output of the optical comb generator was used as the input of an optical injection locking system which consists of two slave lasers. The mechanism of the locked technique is keeping one of the slave lasers in lock with a single line of the reference comb, while locking the other laser in turn to each of the several lines of the comb. The output of the utilized DFB laser diodes were combined and mixed to produce the millimeter wave signals. The total span of the optical comb can exceed (1.8)THz. The SSB noise was reasonable in this experiment. This technique used with changing in the slave lasers types. 400GHz span was produced and the selected lines from an OFCG were separated by an integral multiple of the originating reference frequency. The selected lines were coupled using UTC-PD (Uni-travelling carrier photodiode) [19], which produced Multi-Octave tunable, high power direct optoelectronic millimeter wave. The UTC-PD did not show saturation, so it can be used in experiments with higher produced power. The highest power obtained was at 60 GHz (3dBm), when the input light power was 19dBm. The frequency of the produced millimeter wave signal is a multiple of the reference frequency ( $f = n \times f_{RF}$ ). The block diagram of the experiment is shown in figure 6. The two utilized slave lasers were DFB laser diode (distributed feedback laser diode) and SG-DBR-LD (Sampled – grating distributed Bragg reflector laser diode). The current tuning range of the first one is not large. It can be locked to a specific OFCG line by adjusting its current and temperature. On the other hand, the second laser provides a wider current range which make it useful for multi-octave millimeter wave generation applications

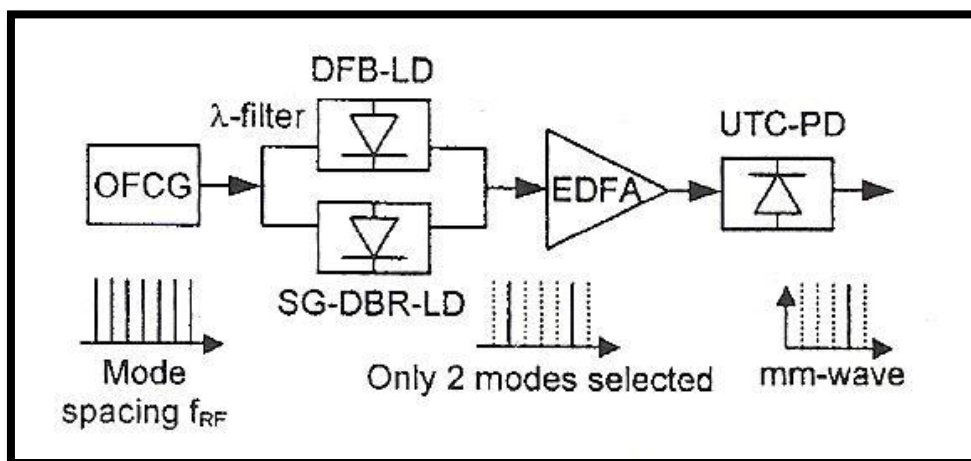


Figure 6: the block diagram implemented in experiment.

**4.2 Optical Phase – Locked Loops (OPLL) :**

Optical Phase – Locked loops is one of the strong suggested techniques used to generate low noise millimeter wave signals by heterodyning two lasers. In this method, it is essential to use a high

quality microwave signal source to provide a references frequency [6].

A new improvement on optical phase locking method was demonstrated in to generate extreme pure millimeter wave signals. The method relies on

cascading three phase locked semiconductor lasers. As in shown in figure 7, a semiconductor optical amplifier was utilized to generate the four wave mixing process from the three cascaded lasers. The four wave mixing was applied to optical phase locked loop to check the frequency separation between the three lasers at each new loop. Another optical phase locked loop was developed to operate at high frequencies. Combining the two phase locked loops and cascading the three semiconductor lasers led to generate high purity millimeter wave signals at frequencies up to 330.566 GHz. The ration between the three lasers frequency set to be 1:2. Due to that ratio, the largest frequency separation increases three times faster than the smallest one. The outputs of the three lasers were combined by 50:50 fiber coupler and semiconductor optical amplifier. After that, 80%

from the coupled optical beams was phase locked to a special stable local oscillator through the first OPLL. The remain 20% was fed to a photodetector to be phase locked to another local oscillator. The error signal from the second phase locking was fed back to the second semi conductor laser. The last two operations were done in the second OPLL. The two OPLL were operated simultaneously. The optical outputs from this experiment were extracted from two ports. One of them after combining the first two semiconductor lasers, while the second one after combining the outputs of the three lasers. This technique can be extended to be applied to systems consist of more than four operated lasers and that may help in generating millimeter wave signals up to 1THz.

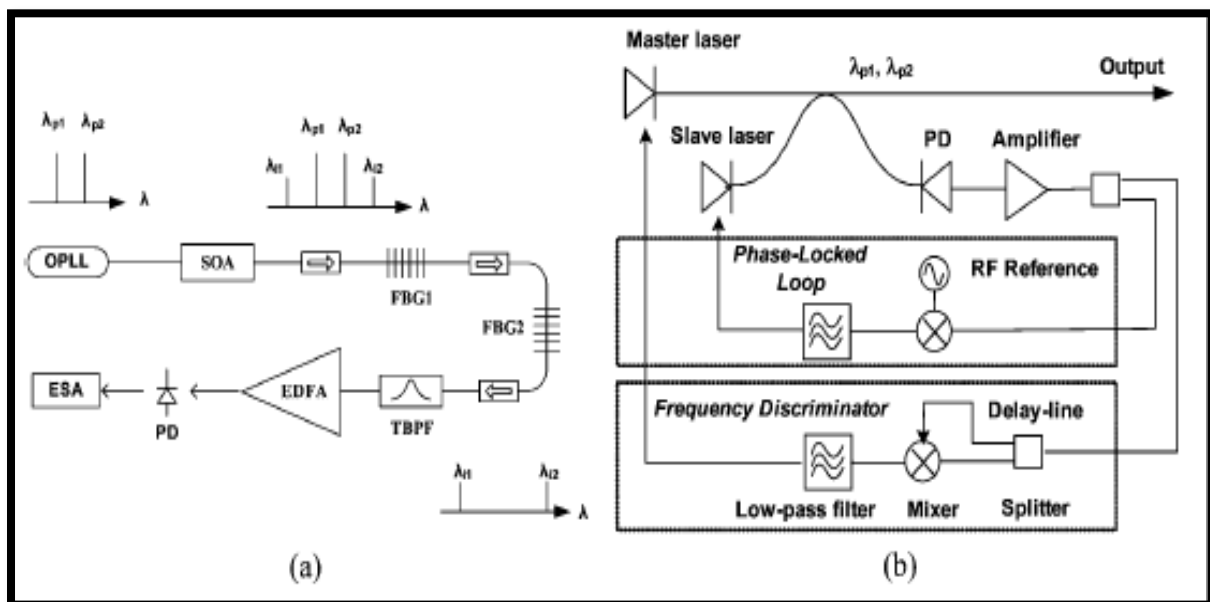


Figure 7: (a) the system used in generating millimeter wave signals. (b) the configuration of OPLL.

## V. Comparison

The comparison of different methods used in generating a low phase noise millimeter wave signals was published and viewed [21]. Four techniques were compared, Multiplication, phase lock loop (PLL), Injection locking (IL), and Injection locking with phase lock loop (ILPLL). It was noticed, through the experiment, that the phase noise of the reference signal could be degraded if residual phase noise is too close to signal noise level. The results of the test shows that the external modulated fiber optics has much lower residual noise. While the best frequency for reference signal distribution through direct modulated fiber optics is the C-band, because there is a lot of margin between the required phase noise and residual phase noise. Another conclusion derived by that experiment is that the generation of a very low close-in to carrier phase noise at MMW frequencies

is achieved most effectively using an ILPLL oscillator, and the Multiplication is the worst. ILPLL has the best long term phase stability (PS) and short term phase stability. IL has the worst long term PS, but the worst short term phase stability is for PLL experiment.

One of the ways applied to improve the frequency acquisition is incorporating a frequency discriminator in the system scheme with a feedback current. The importance of the feedback current is in adjusting the frequency of the master laser at each new loop of the master laser. Grating tuned external cavity semiconductor lasers are a promising signals feeders in optical heterodyning experiments. Their large tuning capabilities and their availabilities at fiber compatible wavelengths gave them this excellence. Low phase noise can be reached by using

this type of lasers because of their intrinsically narrow line widths.

## VI. Contributions in experiments schemes

One of the schemes presented for efficient Transmission in Radio over Fiber field is based on AWG-Based DWDM system [22]. That paper suggested applying a technique in which (WI) wavelength interleaving in conjunction with DWDM will lead to increase the number of served base stations through a single central office. The proposed technique depends on reusing the wavelength and having a simultaneous detection and modulation using electroabsorption modulator.

A new technique to control MMW signals is presented. A true time delay phase shifts of broad band Microwave and MMW signals through optical control is proposed. Continuous and precise phase shift with a range of 360 degrees had been achieved without any loss in the millimeter wave signals. It is important to control the phase variation of propagating wave along a transmission line. The older techniques were based on utilizing semiconductor phase shifter via using transistors (field effect) and PIN diodes. Those techniques suffer from considerable reference insertion loss, and are limited in operation at millimeter wave signals frequencies. Because using two lasers – with different frequencies – to generate and modulate millimeter signals may suffer from true time delay phase shift, it is important to control the phase of the millimeter wave signals by synchronizing millimeter waves to mode locked laser pulse trains. That synchronization between the ultrafast optical pulse trains and millimeter wave makes it easy to control millimeter wave devices. Improvements in the speed and accuracy of controlling the optical delay can lead to use this technique in smart communication systems.

By reviewing several contributions in the field of generating millimeter wave signals, it is observed that various laser types were used as signal sources. Choosing the laser type depends on different factors as the complexity, the phase noise, the cost, and the ability to be integrated with optical systems. The conventional solid-state laser source has low noise level. On the other hand it is expensive and complex. The noise level is higher in laser diodes. When the laser diode is mode locked, it provides high modulation efficiency beside the high noise level. Pure spectral quality, efficient high frequency, and low noise modulation signals can be generated by using mode-locked microchip laser as the main source. Not only that, but also it has a high optical output power which makes it appropriate for high capacity distribution systems. The mode-locked microchip sources are more stable and have low cost.

## References

- [1] S. Kim, H.-C. Ryu, S. Kang, S. Y. Jeong, S. Lee, D. Kang, M. Kwak, S. Choi, M. Paek, and K.-Y. Kang, “*The First Experiment Results of mm-Wave Generation by Photomixing*,” IEEE, THz Technology Team, Gajeongno, Korea, pp. 4244-2120, Jun. 2008.
- [2] A. J. Vieira, “*Mode-Locked Microchip Lasers for Millimeter-Wave Generation for Optically Fed Wireless Systems*,” IEEE MP4, pp. 144-145, 2000.
- [3] T. Hoshida, H.-F. Liu, M. Tsuchiya, Y. Ogawa, and T. Kamiya, “*Subharmonic Hybrid Mode-Locking of a Monolithic Semiconductor Laser*,” IEEE Journal of Selected Topics in Quantum Electronics, Vol. 2, No. 3, pp. 514-522, September. 1996.
- [4] J. Bowers, P. Morton, A. Mar, and S. Corzine, “*Actively Mode-Locked Semiconductor Lasers*,” IEEE Journal of Quantum Electronics, Vol. 25, No. 6, pp. 1426-1439, June. 1989.
- [5] Z. F. Fan, P. J. S. heim, and M. Dagenais, “*Highly Coherent RF Signal Generation By Heterodyne optical Phase Locking of External Cavity Semiconductor Lasers*,” IEEE Photonics Technol. Lett., pp. 719-721, 1998.
- [6] Q. Wang, H. Rideout, F. Zeng, and J. Yao, “*Millimeter Wave Frequency Tripling Based On Four Wave Mixing in a Semiconductor Optical Amplifier*,” IEEE Photonics Tech. Lett., Vol. 18, No. 23, pp. 2460-2462, December 2006.
- [7] R. P. Braun, G. Grobkopf, and D. Rohde, “*Optical Millimeter Wave Generation And Transmission Technologies For Mobile Communications, And Overview*,” IEEE Microwave Systems Conference, CH3577 - 8/95/000 – 0239, 1995.
- [8] Y.-K. Seo, W.-Y. Choi, and A.-J. Kim, “*Optical Millimeter Wave Generation by Locking of Four Wave Mixing Conjugate Modes in DFB Lasers*,” IEEE MH4, 2000.
- [9] H. Schmuck, R. Heidemann and R. Hofstetter, “*Distribution of 60 GHz Signals to More Than 1000 Base Stations*,” Electron. Lett., Vol. 30, No. 1, pp. 59-60, 1994.
- [10] V. Skresanov, I. Kas, E. Okhryamkina, V. Palamarchuk, and L. Tondy, “*Complex Treatment Cardiovascular Disease with a Low Power Millimeter-Wave Radiation*,” MSMW’ 2001 Symposium Proceedings. Kharkov, Ukraine, June 2001.
- [11] J. Yu, M. Huang, Z. Jia, A. Chowdhury, H. Chien, Z. Dong, W. Jian, and G. K. Chang,

- “Arbitrary-Frequency Optical Millimeter-wave Generation for Radio over Fiber Systems,” in IEEE/OSA Opt. Fiber Commun. Conf. (OFC/ NFOEC), San Diego, CA, USA, March. 2010, pp. 1-3.
- [12] L. Goldberg, H.F. Taylor and J.F. Weller, “Microwave signal generation with injection locked laser diodes,” *Electron. Lett.* Vol 19, p 491-493, June. 1983.
- [13] B. Cai, D. Wake and A. J. Seeds, “Microwave Frequency Synthesis Using Injection Locked Laser Comb Line Selection,” IEEE LEOS Summer Topical Meeting on RF Opto-Electronics, 1995, WD2.
- [14] A. Nirmalathas, H, F. Liu, Z. Ahmed, D. Novak, and Y. Ogawa, “ Sub-Harmonic Synchronous Mode-Locking of a Monolithic Semiconductor Laser Operating at Millimeter Wave Frequency,” *IEEE J. Select. Topics Quantum Electron.*, Vol. 3, pp. 261-269, Apr. 1997.
- [15] H. Chi and J. Yao, “ Frequency Quadrupling and Upconversion in a Radio Over Fiber Link,” *IEEE Journal of Lightwave Technol.*, Vol. 26, No. 15, pp. 2706-2711, August. 2008.
- [16] G. Smith, D. Novak, and Z. Ahmed, “ Overcoming Chromatic-Dispersion Effects in Fiber-Wireless Systems Incorporating External Modulators,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 45, No. 8, pp. 1410 – 1415, August. 1997.
- [17] O.P. Gough, C. F. C. Silva, and A. J. Seeds, “Exact Millimeter Wave Frequency Synthesis By Injection Locked Laser Comb Line Selection,” *IEEE/ University College London, Torrington, London WC1E 7JE*, PP. 7803-5558, 1999.
- [18] R.-P. Braun, G. Grosskopf, D. Rohde and F. Schmidt, “ Low-Phase-Noise Millimeter-Wave Generation at 64 GHz and Data Transmission Using Optical Sideband Injection Locking,” *IEEE Photon. Technol. Lett.*, Vol. 10, No. 5, pp 728-730, May. 1998.
- [19] H. Ito, T. Furuta, T. Ito, Y. Muramoto, K. Tsuzuki, K. Yoshino, and T. Ishibashi, “W-band Uni-Travelling Carrier Photodiode Module For High-Power Photonic Millimeter-Wave Generation,” *Electron. Lett.*, Vol. 38, No. 22, pp. 1376-1377, October, 2002.
- [20] R.-P. Braun, G. Grosskopf, D. Rohde, F. Schmidt, and G. Walf, “Fiber-Optic Millimeter Wave Generation at 64 GHz and Spectral Efficient Data Transmission for Mobile Communications,” *IEEE OFC Technical Digest 1998, TuC4*, pp. 17-18.
- [21] A. S. Daryoush, “Phase Coherency of Generated Millimeter Wave Signals using Fiber Optic Distribution of a Reference,” *Microwave Photonics Device Laboratory, Department of ECE, Drexel University, Philadelphia, PA 19104*.
- [22] P. A. Gamage, A. Nirmalathas, C. Lim, M. Bakaul, D. Novak, and R. Waterhouse, “Efficient Transmission Scheme for AWG-Based DWDM Millimeter Wave Fiber Radio Systems,” *IEEE, Photonics Technology Lett.*, Vol. 19, No. 4, pp. 1041 – 1135, Feb. 2007.