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MODELING OF BROADBAND LIGHT SOURCE FOR OPTICAL NETWORK APPLICATIONS USING FIBER NON-LINEAR EFFECT

[1]G GEETHA, [2]I LAKSHMI PRIYA, [3]M MEENAKSHI

[1]Associate Professor, Department of ECE, CEG, Anna University, Chennai, India
[2]Assistant Professor, Department of ECE, MSEC, Anna University, Chennai, India
[3]Professor, Department of ECE, CEG, Anna University, Chennai, India
E-mail: [1]geetha@annauniv.edu, [2]priyaisanaka@gmail.com , [3]meena68@annauniv.edu

ABSTRACT

Vision towards establishing an all fiber configuration is the motivation behind this work. With the increasing need for high capacity communication systems, Broadband sources have become a necessity. Broadband optical sources are an integral part of multichannel high speed fiber optical communication networks based on all-optical WDM and OCDM. FWM (Four-Wave Mixing) effects and SC (Super Continuum) phenomenon in fibers are used in the design of broadband optical sources. The spectral slicing of the broadband spectra has been proposed in literature as a simple technique to create multi-wavelength optical sources for wavelength division multiplexing applications. The objective of this work is to develop an accurate model for simulating FWM and SC based broadband optical spectra and compare their performances. The modeling work is carried out using SIMULINK in MATLAB 7.10.0(R2010a).

Keywords: *Four Wave Mixing, Super Continuum, Non Linearity, SMF, DSF, PCF.*

1. INTRODUCTION

WDMA is a simple, natural approach to harnessing the bandwidth of optical fibers. However with ever-increasing demand to support higher levels of traffic, a pure WDMA for providing network capacity and functionality will not be sufficient, fundamentally limited by the number of useable wavelengths. According to ITU G.694-2, the CWDM uses the frequency range from 1270nm to 1610 nm. With a spacing of 20 nm, the number of CWDM wavelengths that could be realized is limited to 18 which may not be sufficient for accommodating even a moderate number of users. Hence WDM cannot be brought down to the customer premises of small-to-medium sized businesses and residential users, [2]. Therefore another layer of multiplexing is required for future network expansion, where OCDMA could be introduced in the spectral gaps between the WDM channels with appropriate filters, thus allowing hybrid OCDMA/WDMA networks, [2]. The Spectral Amplitude Encoding (SAC) technique is one of the popular technique for OCDMA implementation and requires multiple spectral components. This in combination WDMA, termed as hybrid SAC-OCDMA/WDMA system demands a broadband spectrum. Broadband source realizations available in literature are based on many possible techniques,[11]. The spectral broadening for broadband sources is usually accomplished by propagating optical pulses through a strongly nonlinear device, such as an optical fiber, [4,5]. In this paper, two techniques namely Four Wave Mixing (FWM) effect in silica fiber and Super continuum (SC) phenomenon in Photonic Crystal Fiber (PCF) are used for the design of broadband optical sources.

The FWM phenomena in a single-mode fiber as such imposes a fundamental limitation on the capacity of multi-channel optical communication systems. But FWM being a spectral broadening phenomenon has the ability to distribute energy to new frequency components and hence can be exploited in designing a broad band optical source, [6,7]. Another prominent non linear effect in Photonic Crystal Fibers is the Super Continuum process which generates new frequency components when an intense higher order soliton pulse propagates in a highly non linear medium. The super continuum is generated due to the Soliton fission process and interplay of the other non-linear phenomena [13]. Due to this ability SC

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effect proves to be advantageous to be used in the design of broadband sources.

In the present work, the FWM nonlinear effect in a standard Single Mode Fiber (SMF) and Dispersion Shifted Fiber (DSF) and the SC effect in a PCF are modeled for realizing the broadband sources. The fiber is modeled based on Split-Step Fourier method including linear and the non-linear effects. The introduction and motivation are explained in section 1. The fiber and source models are explained in section 2. The simulation block diagrams and the parameters used are highlighted in section 3. The simulation results are explained and inferences drawn in section 4. The conclusions are highlighted in section 5.

2. SYSTEM MODELING

In section 1, the necessity for a broadband source was highlighted. The FWM and the SC phenomenon in fibers, which distribute the narrowband input optical energy to a wider band are explored and analyzed. The main modules required are narrowband optical sources and appropriate optical fibers. This section deals with the modeling of the linear / non-linear interplay in the optical fiber and the broadband optical source.

2.1 Fiber Modeling

Fiber modeling is based on nonlinear Schrödinger equation (NLSE) which is an approximate scalar form of the wave equation in optical fiber, given by, [9],

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{j}{2}\beta_2 \frac{\partial^2 A}{\partial t^2} - \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial t^3} = j\gamma |A|^2 A - \frac{\alpha}{2} A \quad (1)$$

The Split Step Fourier Method (SSFM) is the technique of choice for solving the NLSE due to its easy implementation and speed compared to other methods, [3]. The block diagram of the SSFM concept is shown in Figure 1. The mathematical terms due to dispersion and attenuation (D) and nonlinearity (N) are separated and decoupled in the NLSE. This decoupling allows the use of the SSFM for solving the NLSE. By looking at the NLSE, the operators *D* and *N* can be written as,

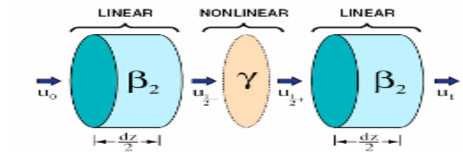

Figure 1 : SSFM Block Diagram

$$D = -\frac{\alpha}{2} - \sum_{m=2} \frac{i^{m-1}}{2^{m-1}} \beta_m \frac{\partial^m}{\partial t^m} \quad (2)$$

and

$$N = j\gamma \left[|A(z,t)|^2 + \frac{2i}{\omega_o A(z,t)} \frac{\partial}{\partial t} \left(|A(z,t)|^2 A(z,t) \right) \right] \quad (3)$$

where $A(z,t)$ is the complex field envelope at step z and time t. The NLSE then can be written in the operator form as, [1],

$$\frac{\partial A(z,t)}{\partial z} = (D+N)A(z,t) \quad (4)$$

$$A(jh,t) = exp[h(D+N)]A\big((j-1)h,t\big) \quad (5)$$

is the solution to the differential equation at step $z=jh$ (j is an integer). The *N* operator multiplies the field solution and is a function of the solution $A(z,t)$. The *D* operator is a differential operator expressed in terms of time derivatives that operate on $A(z,t)$.To reduce the computational time, the operation of *D* is performed in the frequency domain; this transforms the derivatives in the time domain to a multiplication in the frequency domain, [1,3].

2.2 Broadband Source Modeling

The input optical energy is derived from narrowband optical sources like DFB laser arrays, Soliton Lasers, etc. These sources are modeled as ideal sources in Simulink. The FWM efficiency has to be high to realize a broadband source. Hence the input laser wavelengths are selected with equal spacing between. The block diagram of the FWM based source and the SC based source are shown in Figures 2a and 2b respectively.

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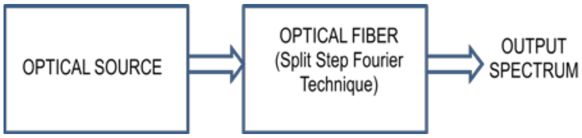
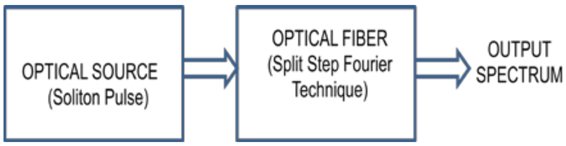


(a)



(b)

Figure 2: Block Diagram
(a) FWM Based Source
(b) SC Based Source

The input for the SC based source is an optical pulse of width 70ps with a hyperbolic secant profile. Photonic crystal fiber with a small core can have their zero dispersion wavelength (ZDW) shifted to a wavelength significantly shorter than the ZDW of standard single-mode silica fibers.[4,5].

3 SIMULATION MODEL AND PARAMETERS

3.1 Fiber Subsystem

The fiber used for the broadband optical source is modeled using SSFM and simulated using MATLAB SIMULINK. For the SMF, DSF and PCF, the simulink blocks will obtain the required input data like the wavelength dependent attenuation, dispersion and non-linearity index for the respective step, after running the initialization m-file. This is required because the fiber parameters listed in Table 1 for SMF, DSF and PCF, hold good only at a specific wavelength of 1550 nm for SMF and DSF and 850 nm for PCF. As the wavelength of the input optical light changes, some of the parameters values also deviate. Since FWM occurs due to the interplay of dispersion and non-linearity, it is imperative that the correct wavelength dependent values for attenuation, dispersion and non-linearity be used in the simulation.

Table 1: Fiber Parameters

FIBER TYPE	SMF	DSF	PCF
DISPERSION PARAMETER (D)	17 ps/nm.Km	-3 ps/nm.Km	2.5 ps/nm.Km
ATTENUATION (α)	0.20 dB/Km	0.22 dB/Km	0.1 dB/Km
CORE RADIUS (r)	5.21 µm	4 µm	1 µm
DISPERSION SLOPE (S)	$0.092*10^{-6}$ ps/nm^2	$0.076*10^{-6}$ ps/nm^2	$1*10^{-6}$ ps/nm^2
EFFECTIVE AREA (A_{eff})	$85*10^{-12}$ m^2	$50*10^{-12}$ m^2	$3.14*10^{-12}$ m^2
NON-LINEAR INDEX COEFFICIENT (n_2)	$2.6*10^{-20}$ m^2/W	$2.35*10^{-20}$ m^2/W	$3*10^{-20}$ m^2/W

For the simulation of fiber of 1Km length using SSFM, 10 sections with step size of 100 m fiber are considered as shown in Figure 3. Each fiber split section shown in figure 3 exhibits linear and nonlinear effects in the sequence shown in Figure 4. The linear and non-linear effect implementation are as shown in figure 5 and figure 6, respectively.

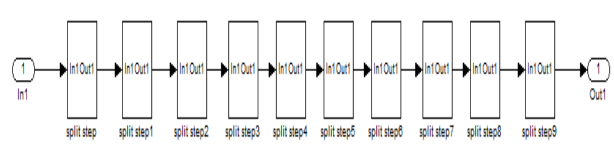


Figure 3: Simulink Step Model Of Fiber

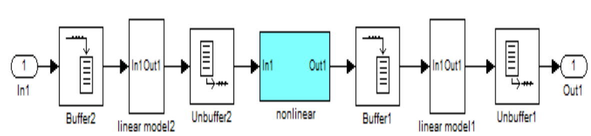


Figure 4: Simulink Model of each Split step

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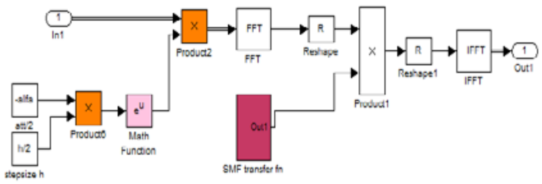

Figure 5: Simulink Model of Linear Fiber Section

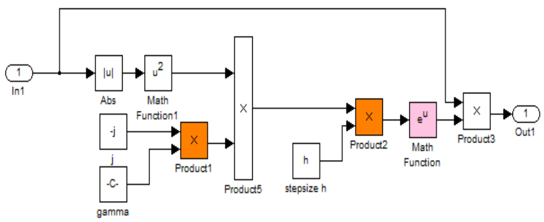

Figure 6: Simulink Model of Non-Linear Fiber Section

3.2 Broadband Source Simulation

3.2.1 Simulation of FWM based broadband source

The simulation blocks used for the design of the broadband source using FWM effect are shown in Figures 7 and 8. The optical energy that enters the fiber comes from an array of three ideal lasers emitting at 1547.478 nm, 1551.086 nm and 1553.763 nm, the corresponding frequencies being 193.864THz, 193.413THz and 193.079 THz. However to work with reasonable speed and sampling accuracy in MATLAB SIMULINK , these carrier signals are generated at downscaled values of (8.5 THz, 8.67 THz and 8.9 THz). Though the carriers are downscaled, the fiber impairments are estimated at the respective actual carrier frequency values and applied in the simulation.

3.2.2 Simulation of SC based optical source

The super continum effect in Photonic Crystal Fiber with the parameter values specified in Table 1 is modeled and simulated as shown in Figure 9.

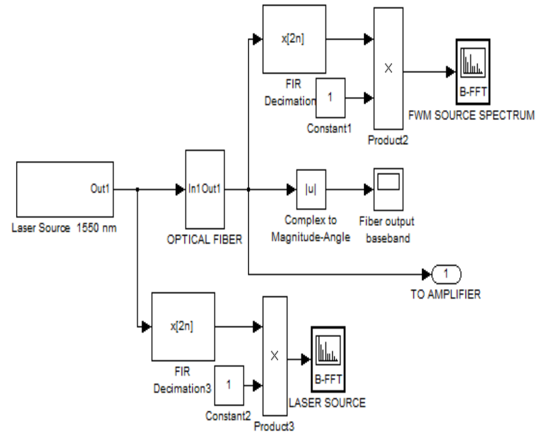

Figure 7: FWM Source- Simulink Model

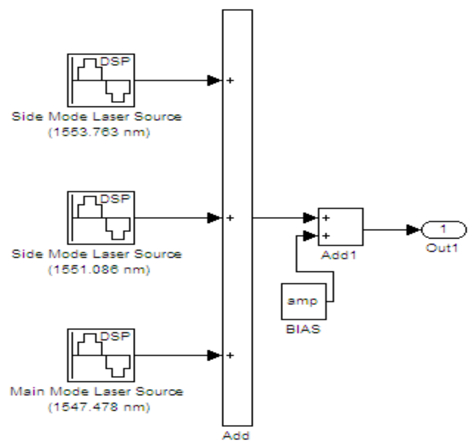

Figure 8: Laser Source used in FWM Source Model

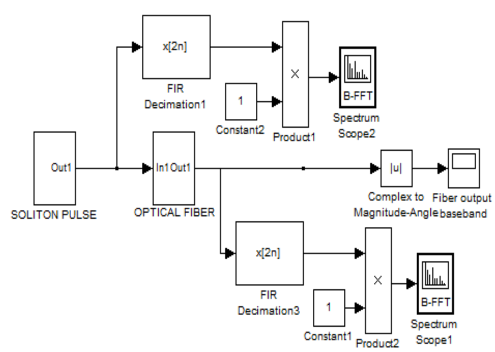

Figure 9 : SC Source- Simulink Model

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3.3 Simulation Parameters and Interrelationships

The different parameters used in the model are interrelated and have to satisfy certain relationships to demonstrate the non-linear effect. These relationships are highlighted in this subsection.

The center wavelength considered is λ_o and is equal to 1551.086 nm. The corresponding frequency f_o is ν/λ_o and ω_o is the radian frequency. ν represents the speed of light. The linear second order dispersion at λ_o is given by,

$$\beta_2(\lambda_o) = -\frac{D\lambda_o^2}{2\pi\vartheta} \quad (6)$$

And the non-linear coefficient γ is given by,

$$\gamma = \frac{2\pi n_2}{\lambda_o A_{eff}} \quad (7)$$

The dispersion length L_D is estimated using,

$$L_D = \frac{T_p^2}{|\beta_2(\lambda_o)|} \quad (8)$$

where T_p is the width of the input pulse. The non-linear length L_{NL} is estimated using,

$$L_{NL} = \frac{1}{\gamma P_o} \quad (9)$$

The non-linear phase ϕ_{NL} is then estimated as,

$$\emptyset_{NL} = \gamma L P_o \quad (10)$$

The fiber length L is 1000 m and the step length is 100 m. For the linear and non-linear effects to maniifest in the fiber the condition is ,

$$L_D << L \quad \text{and} \quad L_{NL} << L \quad (11)$$

For the proper interplay between dispersion and non-liearity, the minimum requirement on the pulse width T_p is given by the condition $L_D = L_{NL}$. Hence, the minimum pulsewidth required, T_{preq} , is

$$T_{preq} = \sqrt{\frac{|\beta_2(\lambda_o)|}{\gamma P_o}} \quad (12)$$

The pulse shape is considered Gaussian and the pulse width T_p is chosen to be less than T_{preq} , in this case 13.45146 ps. The number of samples representing a single pulse is then calculated using T_p / T_s, where T_s represents the sampling period. In order to correctly resolve the output spectra and correlate with the model, the FFT size in the SSFM model as well as in the spectrum analyser is considered as 4096. The total spectral occupancy range of 50 THz is considered and hence the resolvable frequency spacing Δf is 50 THz/4096 ~ 12 GHz. The sampling duration is reciprocal of the total spectral occupancy and hence is 0.02 ps. The width of the input Gaussian pulse is chosen to be 1.28 ps and hence the number of samples per Gaussian pulse is calculated as 64.

P_o represents the power and $v = P_o/\sqrt{2}$ represents the voltage of the signal. The effective length of the fiber L_{eff} is given by,

$$L_{eff} = \frac{1-exp(-\alpha L)}{\alpha} \quad (13)$$

The steps shown in Figure 10 show the calculation of the dispersion and the non-linear coefficient for each of the resolvable frequency and hence the wavelength component.

n = 1: 4096
$\Delta f(n) = \Delta f\,[\,(4096/2) - (n-1)\,]$
$\Delta\lambda(n) = (\,0.8\text{ nm} / 100\text{ GHz}\,) \times \Delta f$
$f(n) = f_o - \Delta f(n)$
$\lambda(n) = \nu / f(n)$
$D(n) = D - \Delta\lambda(n) \times S$
$\beta_2(n) = D(n)\,\lambda(n)^2 / (2\pi\nu)$
$\gamma(n) = (2\pi n_2) / \lambda(n)\ A_{eff}$

Figure 10 : Steps To Estimate Wavelength Dependent Dispersion And Non-Linearity For Simulation

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3.4 Filtering (Spectral Slicing):

From the generated broadband optical signal at the output of the nonlinear fiber the required spectral component can be extracted after amplification using appropriate optical filter for that wavelength. The amplifier and spectral slicing are shown in Figure 11.

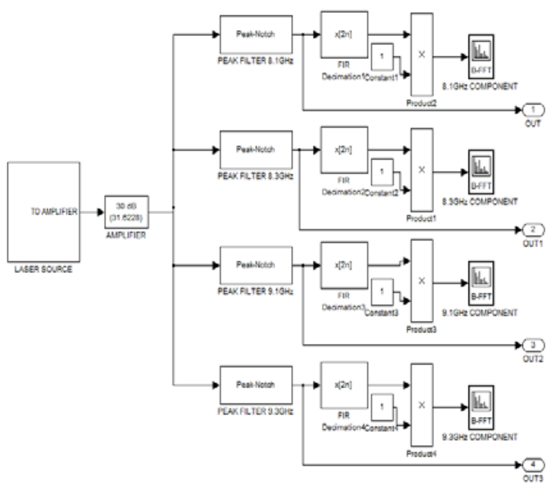

Figure 11: Amplification and Spectral Slicing-Simulink Model

4 SIMULATION RESULTS

4.1 Output Spectrum Analysis of FWM Based Optical Source

As mentioned in the previous section, the generation of broadband signals requires an input source of optical energy and this is obtained using laser sources at 193.079THz (8.5THz), 193.413THz (8.67THz) and 194.079THz (8.9THz) centered at 1550nm. The combined laser outputs that feeds the optical fiber is shown in Figure 13. The total input power from the three sources is 100 mW.

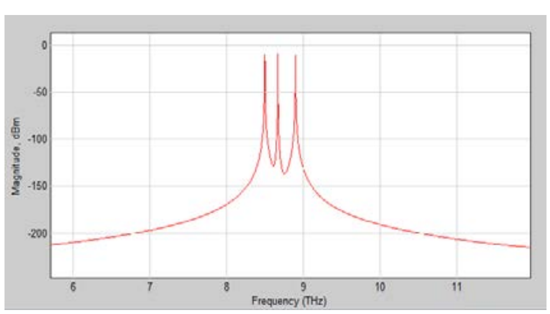

Figure 13 : Input Signal to the fiber with Pin-100mW

The outputs from SMF and DSF obtained through simulation are shown for different combinations of input power (P_{in}) and fiber length (L). These results are given below.

CASE 1: For standard single mode fiber with varying input power (P_{in}):

Overall length of the fiber considered for simulation is 10m with step-size taken as 1m. The results obtained and shown in Figure 14, indicate the distribution of energy to more spectral components when the input power fed to the fiber is increased. This matches with the theoretical expectation and hence validates our model.

CASE 2: Varying overall length L of the Fiber (SMF)

The input power (P_{in}) is maintained at 100mW, and the results shown in Figure 15 were observed at the output of the fiber when the fiber length is varied. The strength of the spectral components are seen to increase as fiber length increases. This again validates the fact that the impact of FWM increases as the fiber length increases. The above results show that for increased input power and increased fiber length, due to the increased fiber nonlinear effect, the output spectrum gets broadened with more spectral components and increase in the strength of these generated components.

CASE 3: Comparison of SMF and DSF

The efficacy of SMF and DSF in generating FWM components is then verified by observing the respective output spectrum with an input power of 50 mW and fiber length of 10m with step-size h=1m. The simulation results obtained and shown in Figure 16, verify the theoretical expectation that the number of FWM components generated in DSF is more compared to that in SMF due to the inherent phase matched condition facilitating the process. The results corresponding to an input power of 100mW and fiber length of 10m was also observed and is shown in Figure 17.

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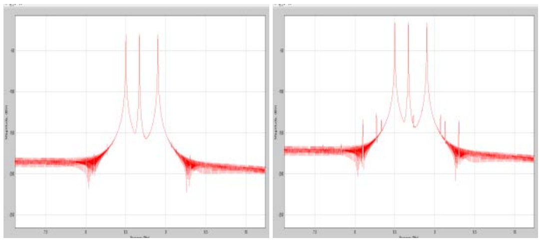
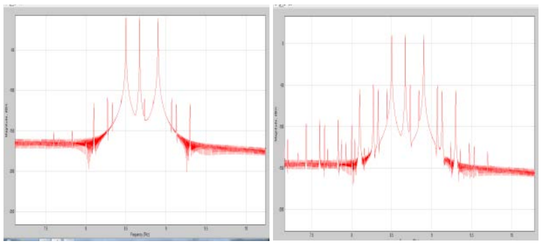
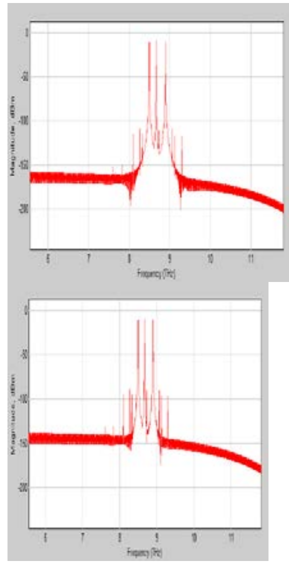


(a) *(b)*



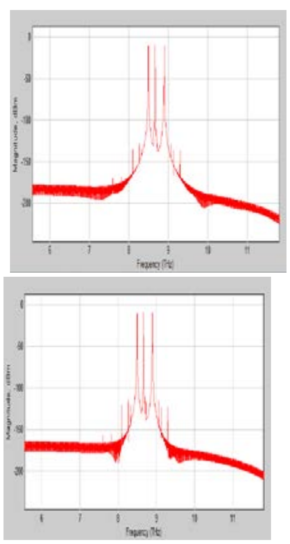
(c) *(d)*

Figure 14: (a) Output Spectrum for P_{in}=10mW
(b) Output Spectrum for P_{in}=50mW
(c) Output Spectrum for P_{in}=100mW
(d) Output Spectrum for P_{in}=1W

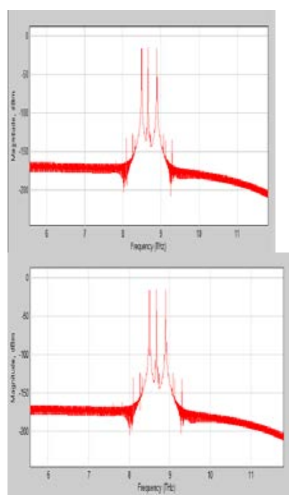


(c) *(d)*

Figure 15:(a) Output Spectrum for L=1m and h=0.1m
(b) Output Spectrum for L=5m and h=0.5m
(c) Output Spectrum for L=10m and h=1m
(d) Output Spectrum for L=100m and h=10m



(a) *(b)*



(a) *(b)*

Figure 16:Input power = 50 mW, fiber length = 10m
(a)Spectrum of SMF
(b)Spectrum of DSF

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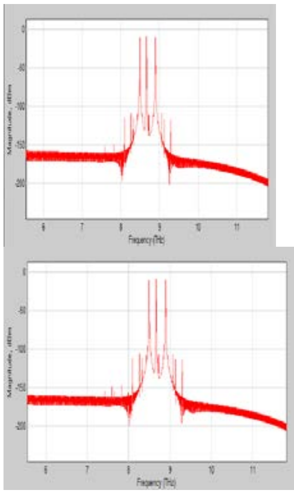

(a) (b)

Figure 17: Input power = 100 mW, fiber length =10m
(a)Spectrum of SMF
(b)Spectrum of DSF

CASE 4: Spectral Slicing

The spectrum after amplifying and spectral slicing of the FWM based broadband optical source output, is then analysed. To compensate for the splitting loss an optical amplifier of gain 30 dB is used in the simulation so that the required spectral components after slicing will have sufficient amplitude. The spectrum at the fiber output which is to be filtered is shown in Figure 18. The filters used correspond to the downscaled frequencies of 8.1 THz, 8.3 THz, 9.1THz and 9.3THz. The actual frequencies are 192.296 THz, 192.688 THz, 194.256 THz and 194.348 THz.. The four filtered components are shown in figures 19 – 22.

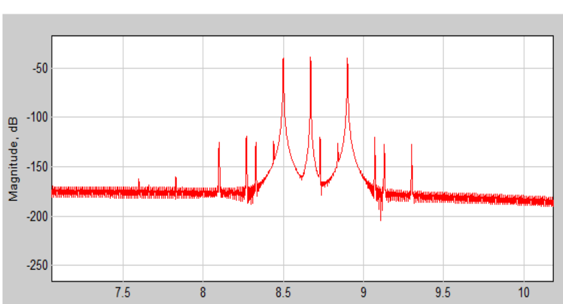

Figure 18: Output Spectrum

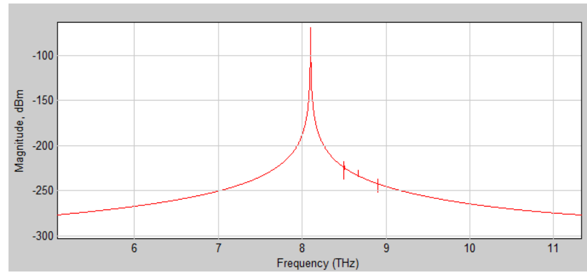

Figure 19: Spectral sliced output at 8.1THz (Actual frequency = 192.296THz)

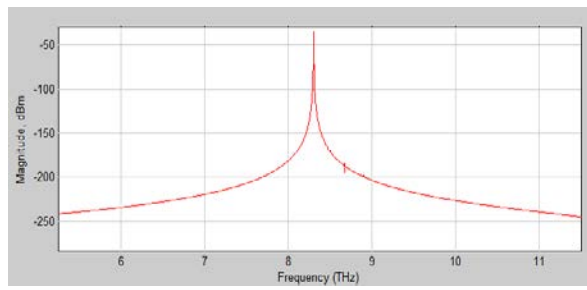

Figure 20: Spectral sliced output at 8.3THz (Actual frequency = 192.688THz)

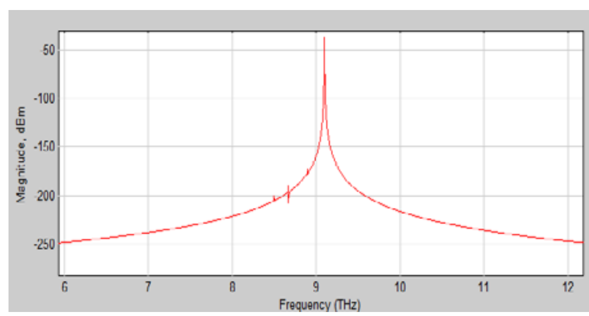

Figure 21: Spectral sliced output at 9.1THz (Actual frequency = 194.256THz)

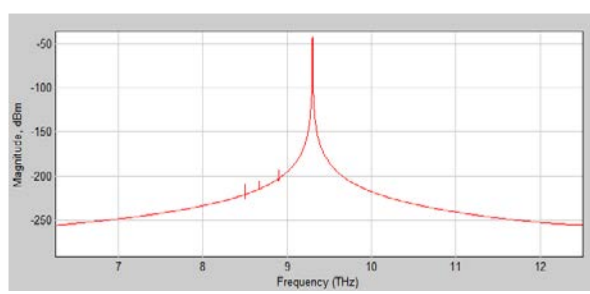

Figure 22: Spectral sliced output at 9.3THz (Actual frequency = 194.348THz)

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4.2 Output Spectrum Analysis of SC Based Broadband Source With PCF

CASE 1: Effect of varying Input Power (P_{in})

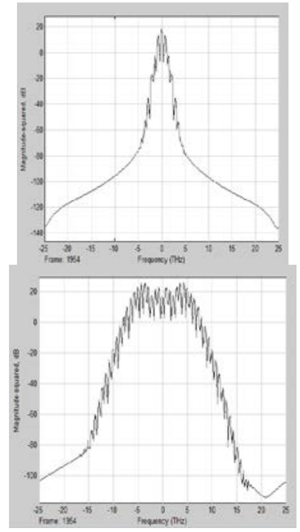
The output spectra of the SC based source using PCF is obtained and is shown in Figure 23 for varied input powers when the overall length of the fiber L=50m with step-size h= 25m.

The spectral broadening effect is more for higher input powers. At 1 W, the 10 dB bandwidth is seen to be less than 10 THz. As the input power increases to 10 W, the 10 dB bandwidth is seen to increase beyond 40 THz. It is further noted that further increase in input power tends to relatively flat spectral broadening.

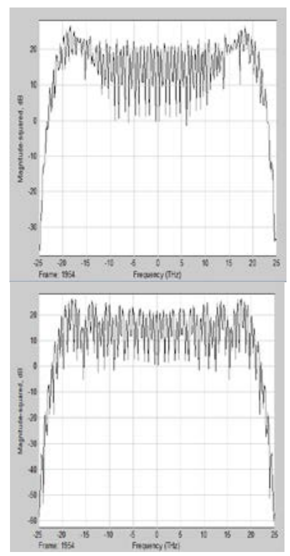
CASE 2: Effect of varying overall Fiber Length (L)

The output spectra of the SC based source is obtained and shown in Figure 24 for varied lengths of the fiber, where the input power is maintained at 5W.

From the results obtained through simulation, it observed that with the increase in the length of the optical fiber, the scale of spectral broadening achieved is increased. However the rate of increase in bandwidth with respect to length in meters is less compared to rate of increase in bandwidth with respect to input power in Watts.



(a) (b)



(b) (d)

Figure 23 : (a)Output Spectrum for Pin=1W
(b)Output Spectrum for Pin=5W
(c)Output Spectrum for Pin=10W
(d)Output Spectrum for Pin=20W

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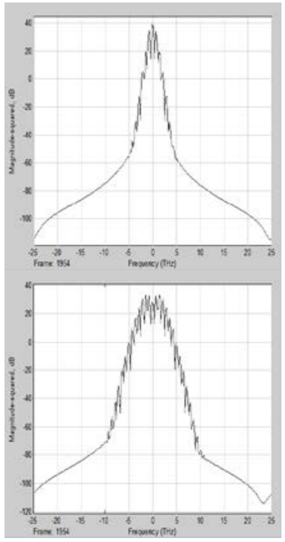
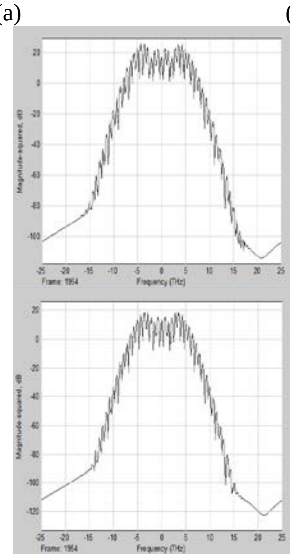


(a) (b)



(c) (d)

Figure 24: (a)Output Spectrum for h=0.5m,L=1m
(b)Output Spectrum for h=5m,L=10m
(c)Output Spectrum for h=25m,L=50m
(d)Output Spectrum for h=50m,L=100m

CASE 3: Spectral Slicing

The output spectrum of SC based broadband optical source for Pin = 20W with L = 50 m, shown in figure 23(d) , is considered for spectral slicing. In a similar manner as that of FWM case, the same components are obtained and are shown in figures 25-28.

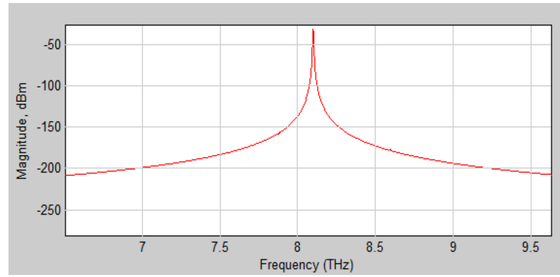


Figure 25: Spectral sliced output at 8.1THz (Actual frequency = 192.296THz)

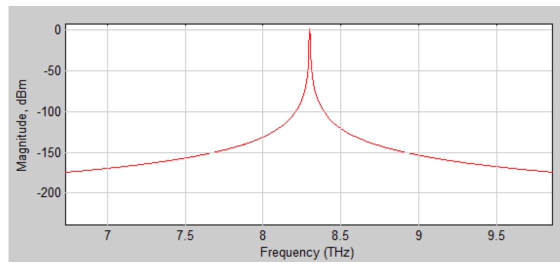


Figure 26: Spectral sliced output at 8.3THz (Actual frequency = 192.688THz)

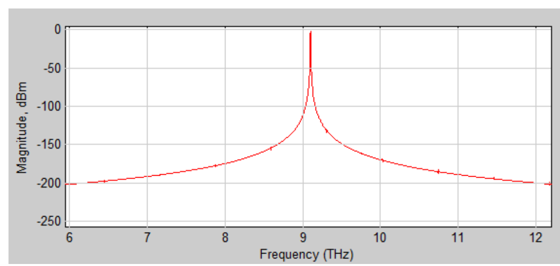


Figure 27: Spectral sliced output at 9.1THz (Actual frequency = 194.256THz)

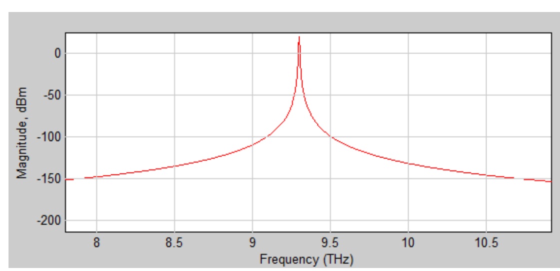


Figure 28: Spectral sliced output at 9.3THz (Actual frequency = 194.348THz)

5 CONCLUSION AND FUTURE WORK

In this work, an accurate model for the optical fiber including its linear and nonlinear behavior is brought out based on the Non Linear

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Schrodinger Equation and simulated. This fiber model is used for realizing broadband optical sources based on Four Wave Mixing and Super Continuum effects. The SC based source proves to be very advantageous due to the broad continuous flat spectra it provides and hence find its applications when the capacity of an optical fiber is to be utilized to the maximum. But it requires very high pump power compared to FWM based source. The FWM based source proves to be very efficient due to its discrete output spectrum and extracting the required spectral component becomes easier. The future work is focused on incorporating the sliced wavelength from these broadband sources in a hybrid WDMA/OCDMA system and the system performance to be analyzed.

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