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# Optical Frequency Comb Generation using Fiber Nonlinearity for WDM-PON

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## Abstract:
Optical Frequency Comb (OFC) can be used as multi carrier source in optical wavelength division multiplexing. The need for large number of tunable continuous wave optical sources can be minimized with the help of OFC, which consists of equidistant optical frequency components. This paper proposes an OFC generator with flattened characteristics for high data rate optical communication using Highly Non Linear Fiber (HNLF). The proposed setup produces an optical frequency comb with 128 flattened frequency comb lines. The difference between maximum and minimum power level among the 128 spectral components is very minimum and the maximum power and minimum power levels are oberved as 22.7454 dBm and 22.74539 dBm respectively.

*Keywords* **—Optical fiber, Optical Frequency Comb, HNLF, nonlinearity**

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## I. INTRODUCTION

In recent years, most of the data traffic in optical access networks originates from video and multimedia services which demands high data rate communication. Wavelength division multiplexed passive optical network (WDM-PON) is one of the promising solutions for this requirement [1, 2]. In a typical WDM-PON, a unique wavelength is allocated to each user which demands the efficient generation of several wavelengths simultaneously. Though tunable laser seems to be an attractive source for such requirement, they are expensive due to the sophisticated technologies needed for their fabrication [3]. Instead multi-carrier generation techniques can be employed to produce a number of spectral components from a single laser source.

OFC is an optical spectrum which consists of distinct and equally spaced spectral components. It significantly favors broadband communication system and the main purpose of using optical frequency comb in such system is, they can generate dozens of spectral lines from a single frequency input of a continuous wave laser. OFC can be used instead of the laser arrays which are conventionally employed at the transmitter end of WDM-PON for the generation of number of wavelength channels [4].

In the past decade, several techniques have been proposed to generate OFC using mode locked laser, micro resonators, electro - optic modulation and four wave mixing. In the proposed method optical frequency comb is generated using continuous wave laser, HNLF and mach-zehnder modulators. HNLF is used as the main component in this work to generate OFC, as it supports Four Wave Mixing (FWM) which is one of the nonlinear phenomena takes place in the optical fiber [5, 6]. If light waves at three different frequencies f1, f2 and f3 are propagating simultaneously in optical fiber, the nonlinear effect that led to the intensity dependent refractive index results in the generation of signals at frequencies $f_1 \pm f_2 \pm f_3$ and this nonlinear effect is known as FWM. It is necessary to minimize FWM effects in WDM systems as it may result in severe cross talk among different channels. However, this effect can be used positively for optical frequency comb generation. HNLF with very high nonlinear coefficient is designed first using OptiFiber simulation tool and with the help of designed HNLF and cascaded modulators, optical frequency comb generator with flattened characteristics is constructed using OptiSystem simulation tool.

This paper is organized as follows. Section II describes the highly nonlinear fiber for the proposed OFC generator and the design of the proposed HNLF. OFC generation has been illustrated in Section III. Simulation results were discussed in Section IV.

## II. HIGHLY NONLINEAR FIBER

In optical system communication, there are different types of fibers for different applications. One such kind of fiber is the HNLF. Nonlinear coefficient 'γ' that decides most of the nonlinear behaviours in optical fibers is improved significantly in HNLFs by restricting the optical mode to a narrow central region. Refractive index and nonlinear coefficient of an optical fiber are expressed as,

$$n = n_0 + n_2 I$$

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$$

where $n_0$ - linear refractive index ,
$n_2$ - nonlinear refractive index
$I$ - power density of the light signal
$\lambda$ - wavelength
$A_{eff}$- effective area of the fiber

Fiber profile shape, core and cladding sizes and refractive indices can be altered to design such fibers [7, 8]. Highly nonlinear fibers can be used to generate optical frequency comb by encouraging four wave mixing in the fiber. Fig. 1 shows a simple highly nonlinear fiber and standard single mode fiber. The narrow core diameter and increased relative refractive index difference can be observed in the figure. The nonlinear refractive index coefficient of the highly nonlinear fiber is greater than 10 $W^{-1}$ $km^{-1}$ and it mainly depends on the effective area of the fiber.

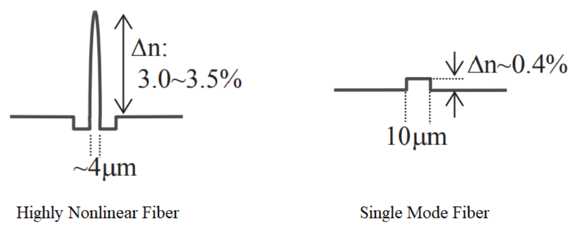


Fig.1 Comparison of HNLF and SMF refractive index profile

HNLF for the proposed OFC generator was designed using OptiFiber software. The designed fiber refractive index profile was flat at its top and it includes five regions. Refractive index and width of Region 0 are 1.483 and 1.8 µm. Region 1 has the width of 0.5 µm and refractive index value of 1.428. Region 2 width is 0.75 µm and refractive index is 1.44692. Width of Region 3 is 0.71 µm and graded index profile is used with alpha peak as the function. Region 4 has the width of 58.7 µm and refractive index value of 1.44692. The designed highly nonlinear fiber is shown in Fig. 2.

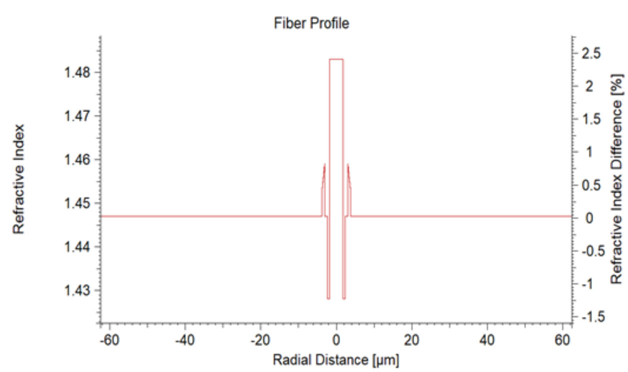


Fig. 2 Refractive index profile of the proposed HNLF

Region 0 is the core of the fiber and the width of it is 1.8 µm. Usually the width of the core should be small for HNLF, approximately less than 2 µm. If a fiber has smaller core it will exhibit high nonlinear characteristics since when the size of the core gets smaller the power density will be high and the nonlinear effects in the fiber will increase. Confinement of the mode field in the proposed HNLF is shown in Fig.3.

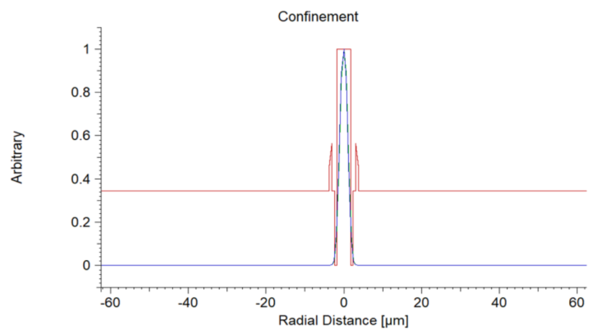


Fig. 3 Mode confinement in the proposed HNLF

Fig. 4 shows the effective mode area of the designed fiber. Effective mode area in optical fiber denotes the area over which the light energy in a mode is effectively distributed in the transverse direction of fiber. For the proposed HNLF, $A_{eff}$ is around 16 µm$^2$ at 1.55 µm. Significance of this small mode area is that the optical intensities for a given power level will be high and it guarantees that the nonlinear effects will be high in the designed fiber.

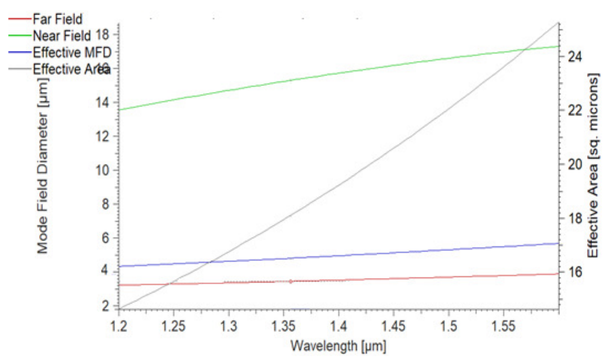


Fig. 4 Effective area of the proposed HNLF

Fig. 5 shows the plot between nonlinear refractive index and wavelength for the designed HNLF. At the wavelength 1.55 µm, $n_2$ is measured as 2.56e$^{-20}$ m$^2$/W.

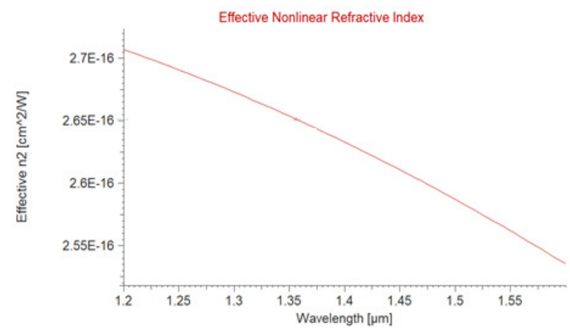


Fig. 5 Nonlinear refractive index of the proposed HNLF

Fig. 4 and Fig. 5 clearly shows that the proposed HNLF will exhibit high nonlinear coefficient. The obtained parameters such as effective area, nonlinear refractive index of the proposed HNLF can be used in OptiSystem software for the OFC generator layout simulation.

## III. OFC GENERATION

Block diagram of the proposed OFC generator is shown in Fig. 6. It consists of Continuous Wave (CW) laser, cascaded mach-zender modulators, sine generators, optical hard limiters and highly nonlinear fiber. OFC is generated by passing the output of CW laser to the cascaded mach-zehnder modulators and the output of cascaded modulators is then given to the designed HNLF where FWM occurs. Electrical sine wave signals with different frequencies and 90º phase are given to both the modulators and the second modulator is used to get more spectral lines. Signal from HNLF is finally passed through optical hard limiter, which gives equally spaced frequency lines as the output.

Fig. 7 shows the simulation layout for the OFC generator. The signal from cascaded mach-zendermodulators is passed through an optical fiber, which has the nonlinear coefficient of 12.26 W$^{-1}$ km$^{-1}$ and length of 1 km. The nonlinear coefficient used was calculated using the parameters such as effective area and nonlinear refractive index which are obtained from OptiFiber tool.

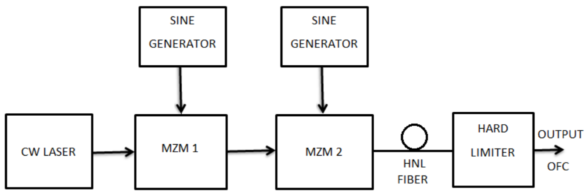


Fig. 6 Block diagram of the proposed OFC generator

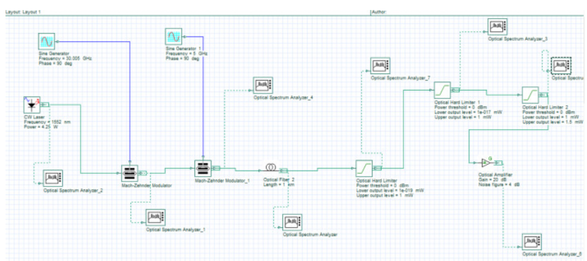

Fig. 7 Layout for OFC generation

The optical fiber component in Optisystem thus attains the characteristics of the HNLF as the parameters measured in OptiFiber are imported to OptiSystem. Four wave mixing process consequently takes place in the fiber and more spectral lines are generated. In order to achieve flatness, the output is passed through optical hard limiters. This component limits the level of the output signal to a user defined range. Three hard limiters are used in the proposed method and as a result of this a flat frequency comb was obtained.

## IV. RESULTS AND DISCUSSION

A single laser source is used in this work to obtain many frequency comb lines. The output of the continuous wave laser used in the proposed OFC generator is shown in Fig. 8. More number of laser sources also can be cascaded to obtain large number of comb lines.

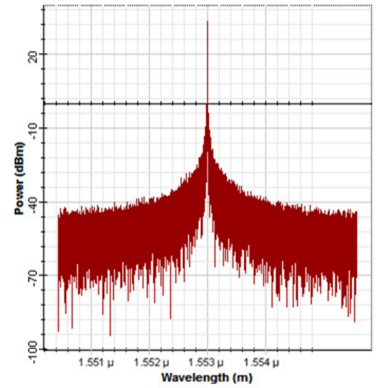


Fig. 8 CW Laser output

When CW Laser is passed through the mach-zehnder modulator 1, output of nearly 7 spectral lines was obtained and around nearly 40 comb lines were obtained at the output of mach-zender modulator 2. Fig. 9 shows the output of mach-zehnder modulators. The output of the Mach-zehnder modulator 2 is acting as the input to the optical fiber.

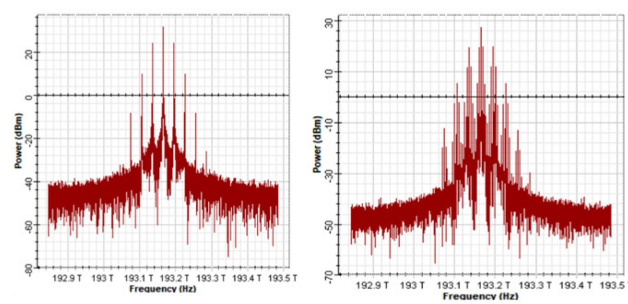


Fig. 9 Output of mach-zehnder modulators

Fig. 10 shows the output signal from the HNLF. Around 128 spectral lines were generated as four wave mixing occurred in the HNLF. In order to get flattened comb lines optical hard limiters were used with required threshold values. Fig. 11 shows the output of the cascaded hard limiters and the flattened spectral lines can be clearly observed from the figure.

  

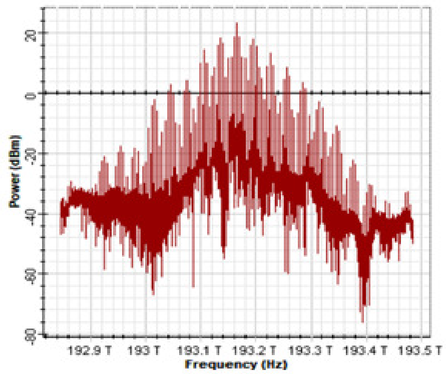


Fig. 10 HNLF output

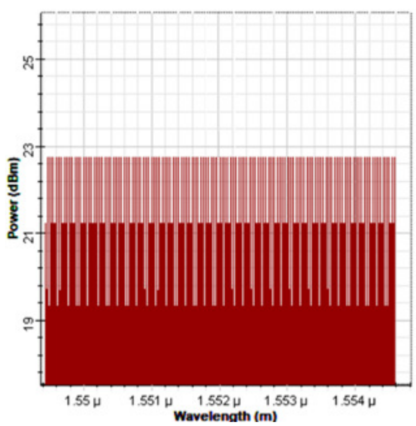


Fig. 11 Generated OFC with 128 spectral lines

Nearly 40 spectral lines were given as input to HNLF, which possess highly nonlinear characteristics, and due to strong four wave mixing 128 equally spaced spectral lines were generated. The difference between maximum and minimum power level among the 128 spectral components is very minimum and the maximum power and minimum power levels are oberved as 22.7454 dBm and 22.74539 dBm respectively.

## V. CONCLUSION

Optical frequency comb with 128 flattened, equally spaced spectral lines were generated using highly nonlinear fiber and cascaded mach-zehnder modulators. Highly nonlinear fiber was used as the key element for the proposed optical frequency comb generator. OptiFiber simulation tool was used to design highly nonlinear fiber. The highly nonlinear fiber design was optimized in such a way that the effective nonlinear refractive index in the order of $10^{-20}$ $m^2/W$ was achieved. The layout for optical frequency comb generator was simulated in OptiSystem software. As the optical fiber has very high nonlinear coefficient, which results in four wave mixing, 128 spectral lines were generated in the fiber. Optical frequency comb with 128 equally spaced and almost uniform power level spectral components thus have been generated from a single laser source.

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