In-Fiber Intrinsic Optical Amplifier

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Abstract - **It has been found by continued research, that if optics through fiber (SM/MM) interacts with (radio frequency) RF with particular frequency of exponentially decreasing magnitude then the optical power follows RF wave shape as envelope. It is also a fact the interaction length between optics and RF is predesigned and fixed for a particular In-fiber amplifier setup. This is the solution of nonlinear Schrodinger Equation (NLS) with a proper trial solution, and the RF magnitude, frequency and interaction length can be derived. Like microwave travelling wave tube (TWT), this In-fiber amplifier has an intrinsic bandwidth and a fixed gain for a particular amplifier structure. Hence gain-bandwidth product for the particular amplifier is fixed. At the output of the interaction length the optical wave is modulated with RF as envelope and the output depends on envelope power. Hence this is analogous to the continuous bunching of electrons with RF as found in microwave TWT. The RF field required in the present case is of an order 5 X 10^5 V.m^{-1} with 2 MHz frequency and this high field is created by producing RF of sufficient magnitude along the surface of the fiber in the axial direction. Besides, the distributive resistances created in each section of the interaction length can be etched on the semiconductor surface of the coaxial tube and the space between semiconductor tube and fiber is coated with ferrite to enhance high frequency magnetic field. Finally, the root cause behind modulating the optical wave with RF is the nonlinear optical phenomena (Kerr Effect) i.e. the variation of refractive index of fiber media with sufficient electric field.**

I. INTRODUCTION

IN an earlier investigation it has been concluded with repeated experimentation that, a change in RF in the range 1 – 3 X 10^{-4} is visible within the optical fiber due to nonlinear Kerr effect when the electric field within the fiber is in the permissible (below dielectric breakdown field) range 10^6 – 6 X 10^6 v/m [1,2]. But the experiment was performed with 100 metres of fiber in a single spacing capacitive setup subjected to nearly 200 Volts DC, and AC, 50 Hz. To generate the same order of field by a micro structure, experiment has been done with RF (10 – 50 MHz) current carrying conductors so that the high frequency magnetic field after focused by ferrite lens cause induced electric field whose RMS magnitude is of the same order as above [3,4]. Based on the same principle, an electrical micro circuit is tried to be developed which creates gradually (exponentially) decreased electric field regions within the fiber. In this process an RF and optics interaction length of 15m has been created where RF field decreases exponentially with length of the fiber. This causes optical power to be amplitude modulated with RF and thus the output optical power is found to be increased by 30dB, for our particular design.

II THEORY

To derive the evolution of envelope of optical power we need to consider nonlinear Schrodinger (NLS) equation [5]:

$$-j\frac{\partial u}{\partial z} = \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + N^2|u|^2 u - j\left(\frac{\alpha}{2}\right)u \qquad [1]$$

Where, u(z,t) is the envelope of optical power
N is the order of solution, here N = 1
The envelope gradually grows is z direction i.e. along fiber length.

α is the attenuation of fiber, here, α = - 0.8 nepers.m^{-1} $|u|^2$ is the induced wave within fiber, here the RF electric field.

Here, in equation [1] the first term $\frac{1}{2}\frac{\partial^2 u}{\partial t^2}$ represents group velocity dispersion effects of the fiber.

The second term $|u|^2 u$ is the nonlinear term and if u is considered to be the electric field variation in fiber then $|u|^2 \alpha \Delta n$ where Δn is the change in refractive index within fiber.

The third term $\left(-j\left(\frac{\alpha}{2}\right)u\right)$ represents the effect of energy loss. If $\alpha \langle 0$, there is energy loss

Let, us now consider the trial solution for NLS as:

$$u(z,t) = e^{\beta z}.Sin(\omega t)$$

Now, using this trial solution is equation [1]; we get relations:

$$-\frac{1}{2}\omega^2 + |E|^2 = 0 \qquad [2]$$

And, $\beta = \frac{\alpha}{2}$ [3]

From equation [2], we get

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$$\omega = \sqrt{2}E_0 \qquad [4]$$

and, from equation [3], we get

$$\beta = \frac{\alpha}{2}$$

As $\alpha = -0.8, \beta = -0.4$

Again, for a overall gain of optical power of 30dB,

$$e^{-0.4\times z} = e^{-6}$$

or, 0.4 X z = 6

or, z = 15 meter

Similarly, in equation [4] we put a satisfactory value

$$E_0 = 6\times 10^6 \text{V.m}^{-1}$$

Hence, $\omega = \sqrt{2}.6\times 10^6 \text{Hz}$

$$= 8.4\times 10^6 \text{Hz}$$

Where, ω is the RF angular frequency.

Now, if we consider a fiber (SM/MM) section of 15 meters and after every 1.5cm along fiber length, the RF field diminishes by a factor $e^{-0.06}$, then after an interaction length (between RF and optics) of 15 meters, the output power is calculated as:

$$P_0 = \frac{E^2}{2\times R_{wave}}\times \pi r_{core}^2 \qquad v^2.\Omega^{-1} \qquad [5]$$

Where E : average electric field between starting and ending of interaction length.

$$R_{wave} = \sqrt{\frac{\mu_0}{\varepsilon_{fiber}}}\Omega = \text{wave impedance of fiber media}$$

Where, $\varepsilon_{fiber} = 3.81\times 8.854\times 10^{-12}\text{F/m}$

μ_0 = Permeability of free space

$R_{wave} = 217\Omega$

So, $P_0 = 3.61$ Watt

Hence, if we input an optical power of 10mW, the output power is few watts.

In the second part of our theoretical analysis, we deal with the RF current required at the surface of the ferrite coated 15 meters strip of fiber. There are 100 sections of fiber with 15cm each and each section current is given by:

$$I_n = e^{-0.06\times n}$$

Where I_n is the current in the nth section. Due to RF current $I_n\text{Sin}(2\Pi ft)$ where, f = 2MHz, the magnetic field induces a RF electric field given by [2,3]:

$$E = \frac{2\Pi A\mu_0\mu_{ferrite}I_n f}{R}.\text{Cos}(2\Pi ft)\ \text{V.m}^{-1} \qquad [6]$$

Where R : core dia of fiber (MM) = 200μm

$\mu_{ferrite}$: permeability of ferrite = 5 X 10^4

μ_0 : permeability of free space = 1.6 X 10^{-6} Henry. m^{-1}

A : cross section area of fiber = 16 X 10^{-8} m^2

I_n : Amplitude of current in nth section of fiber

And, we need I_1 = 100A, to create an electric field of 5 X 10^6 Vm^{-1} as calculated from equation 6.

Now, $I_n = 100e^{-0.06 X n}$ A [7]

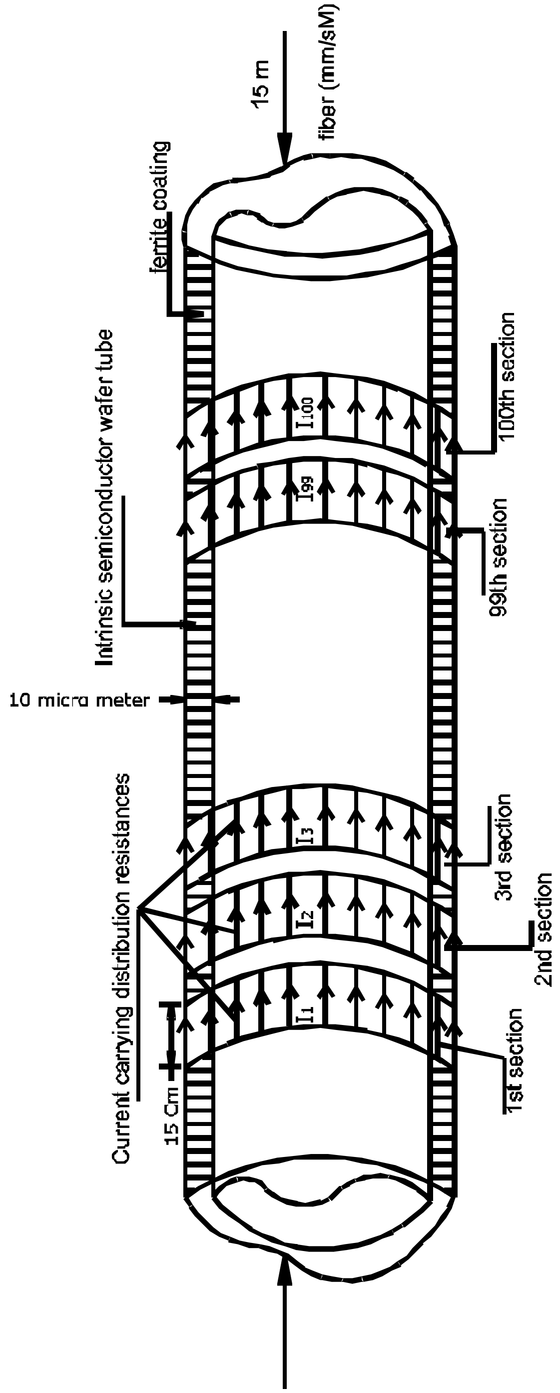

Fig.- (1): FIBER AMLIFIER SETUP

III. DESIGN OF THE AMPLIFIER

The design of amplifier setup is shown in figure 1. The fiber (SM/MM) is drawn through a semiconductor wafer and the portion between two coaxial cylinders is filled with ferrite material. The outer cylinder semiconductor wafer surface is etched with distributive resistance conducting strips along axis of the fiber. Each section of fiber is fitted with 100 strips. Hence, for the 1st section the current in each strip is

1A at 2 MHz and, thus, for nth section the current in each strip is $I_{Sn} = e^{-0.06 X n}$. The separation between two consequtive sections is maintained at 1μm.

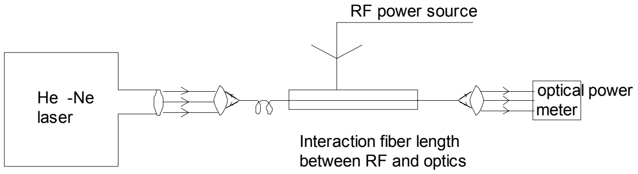

Fig.- (2): EXPERIMENTAL SETUP

IV. EXPERIMENTAL SETUP

The experimental setup is shown in figure 2. The fiber (MM/SM) is coupled with laser (He-Ne) source and the optics has been guided by the fiber to the interaction region between optics and RI and the output is measured by an optical power meter.

V. IN FIBER AMPLIFIER

Using a large number of field decremental electrical circuits (100 sections) in the interaction length between RF and optics, it is found that the increase in power of optics is of considerable amount and nearly about 30dB. The experiment carried out with lesser electric field in each section is found to produce gain of about 20 (2dB). Like travelling wave tubes in microwave this amplifier has an intrinsic bandwidth and this can’t be changed. Hence, for a particular setup gain bandwidth product is constant.

VI. CONCLUSION

Here a new type of In-fiber amplifier has been successfully studied and tested which is developed on the principle of interacting RF electric field of sufficient amplitude and designed frequency with optical wave in fiber over a designed length of fiber. This travelling wave tube is designed to give an amplification of 30dB and its intrinsic gain-bandwidth product is fixed. The fiber may be of any type Single mode or multimode. With the increase of active optical power, the noise power will also increase and the In-fiber amplifier coupled with a filter may reduce the noise power. It is also to be noted that all the current carrying strips are supplied by the same source with 5000 Watts of power. Lastly, with the increase of number of sections from 100 to 1000 along fiber length the noise elimination improves. The work has been supported by A.P.C Ray Polytechnic, Jadavpur, Kolkata – 700 032, authorities who provided all the facilities to carry out the work.

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