Using modified Mach-Zehnder interferometer to get better nonlinear correction term of an isotropic nonlinear material

Ashish Pal* **and Sourangshu Mukhopadhyay****

Department of Physics, The University of Burdwan,
Golapbag, West Bengal, 713104, India
**E-mail: shib_08@yahoo.com; **e-mail: sourangshu2004@yahoo.com*

Received November 12, 2008

Nonlinear materials have been well established as photo refractive switching material. Important applications of isotropic nonlinear materials are seen in self-focusing, defocusing phenomena, switching systems, etc. The nonlinear correction term is basically responsible for the optical switches. Mach-Zehnder interferometer (MZI) is a well-known arrangement for determining the above correction term, but there are some major problems for finding out the term by MZI. We propose a new method of finding the nonlinear correction term as well as the second order nonlinear susceptibility of the materials by using a modified MZI system. This method may be used to find out the above parameters for any unknown nonlinear material.

OCIS codes: 190.0190, 190.7110, 200.0200.
doi: 10.3788/COL20090707.0624.

Nonlinear material (NLM) is being more and more promising as it has a tremendous applicational role in photonic switching systems and many other optical devices[1,2]. Mach-Zehnder interferometer (MZI) is also regarded as a very potential optical device for many interferometric purposes, e.g., measurement of optical characteristics and developing optical logic circuits, etc. MZI can also be used for measuring the nonlinear correction term in its refractive index, but there lies the problem of requiring high intensities of laser light for such measurment[3−5]. Many photonic devices have already been developed based on NLMs[6,7]. In this regard, we propose an alternative approach of measuring the nonlinear correction term of any unknown material. For this purpose, the MZI is used with a little modification. In one arm of the MZI, a suitable electro-optic modulator (EOM) is used while the NLM is not used. The modified Mach-Zehnder system can therefore be used with lower intensity of laser light.

Figure 1 shows the experimental setup. The light coming from an intense source is divided by the beam splitter M into two different beams. One of the divided waves is sent through the path OAB. Along this path, the NLM (the refractive index of which is to be measured) is placed. The width of the NLM is x_3. So the optical path traversed by light through the NLM is $n'x_3$, here n' is the refractive index of the material, which can be represented as $n' = n_0' + n_1 I$, where n_0' is the constant term of the nonlinear refractive index of the material, n_1 is the nonliner refractive index, I is the light intensity. The rest of the optical path traversed by light wave from O to T point in the same arm is n_0x_2, where n_0 is the refractive index of the air and x_2 is the geometrical path length of $OABT$ excluding that through the NLM. So, the total optical path traversed by the light beam to reach T through the NLM is $n_0x_2+n'x_3$. The other splitted wave simply passes through the two mirrors M_1 and M_2 along the path OA^1B^1T. The optical path traversed by the light wave to reach T through M_1 and M_2 is n_0x_1, where x_1 is the geometrical path along OA^1B^1T. This path may be balanced with $n_0x_2 + n'x_3$ by the use of suitable compensator if required. Now at the point T, a certain phase difference due to the path difference between two light waves will occur, which depends upon the intensity of the coherent laser source.

The path difference will be zero when $n_0x_1 = n_0x_2 + n'x_3 = n_0x_2+(n_0'+n_1I)x_3$. Therefore the path difference between n_0x_1 and $n_0x_2 + n'x_3$ can be changed with the variation of input intensity. As a result, an interference pattern will be obtained at the point T. This pattern can be changed from bright to dark or *vice versa* by the variation of intensity I. This variation of output interference result can be used for the determination of the nonlinear correction term of the NLM. By measuring the intensity level of the coherent laser source, when the maximum and minimum intensities of the interference pattern are received at the output T, one can get the value of the nonlinear correction term with the following mathematical approach.

The electromagnetic light wave coming form the source along the path $OABT$ has the phase term $k_0n_0x_2+k_0n'x_3$ at the point T, where k_0 is the wave number of the light in air. As $n' = n_0' + n_1I$, the equation of this wave at T can be expressed as

$$\begin{aligned} E_1 &= E_{01}\cos\{\omega t - k_0(n_0x_2 + n'x_3)\} \\ &= E_{01}\cos[\omega t - k_0\{n_0x_2 + (n_0' + n_1I)x_3\}], \quad (1) \end{aligned}$$

where E_{01} is the amplitude of the electric field of the light passing through the material. Also the other splitted wave traveling through OA^1B^1T (which is fully an air medium) gets the phase value $k_0n_0x_1$ at T. Considering the same amplitude with the first wave, the equation of the second wave at T can be written as

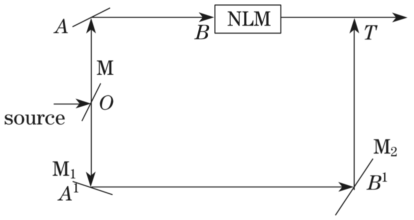

Fig. 1. Experimental setup of MZI.

$$E_2 = E_{01}\cos(\omega t - k_0 n_0 x_1). \quad (2)$$

After superposition of the two waves, the resultant field becomes

$$E = E_1 + E_2. \quad (3)$$

The intensity of the output is the maximum when the phase difference of the two splitted waves is $2N\pi$ and at that situation,

$$k_0[n_0 x_2 + (n_0' x_3 + n_1 I_1 x_3) - n_0 x_1] = 2N\pi, \quad (4)$$

where N is an integer, and I_1 is the respective intensity of the light beam in the path $OABT$ for getting the maximum intensity at the resultant interference pattern.

The resultant intensity is the minimum when the phase difference of the two splitted waves becomes $(2N{+}1)\ \pi$, i.e.,

$$k_0[n_0 x_2 + (n_0' x_3 + n_1 I_2 x_3) - n_0 x_1] = (2N+1)\pi, \quad (5)$$

where I_2 is the required intensity of the light at $OABT$ path for getting the minimum intensity of the resultant interference pattern. From Eqs. (4) and (5), we can obtain

$$k_0 n_1 (I_2 - I_1) x_3 = (2N+1)\pi - 2N\pi, \quad (6)$$

i.e.,

$$\Delta I = I_2 - I_1 = \pi/(k_0 n_1 x_3), \quad (7)$$

which is the amount of intensity required to convert a dark pattern into a bright one. Now by using a suitable photo detector at the output, the bright dark situation can be identified accurately with the variation of input intensity level. If the intensity levels I_1 and I_2 are measured, the numerical value of the nonlinear correction term n_1 of an isotropic material and as a whole the refractive index of a NLM can be measured using Eq. (7).

From the above expression of ΔI, it is clear that, as the value of n_1 is very small, the light intensity required for the conversion from the brightest interference to the darkest one is very high. The availability of the necessary laser is really difficult for supporting the intensity levels.

If the well known NLM CS_2 (for which n_1= 3.10 $\times 10^{-18}$ m^2/W) is used, then taking a light of wavelength λ = 800 nm, a NLM thickness of x_3 = 1 cm, it can be found that the intensity required for converting the brightest output at T to the darkest one is $\Delta I = \dfrac{\lambda}{2n_1 x_3}$=$1.29\times 10^{13}$ W/m^2. This is an exceptionally high value for a continuous-wave (CW) laser source to provide. The new modified MZI proposed here can obtain the required value of the nonlinear correction term of an unknown NLM with a much smaller value of intensity.

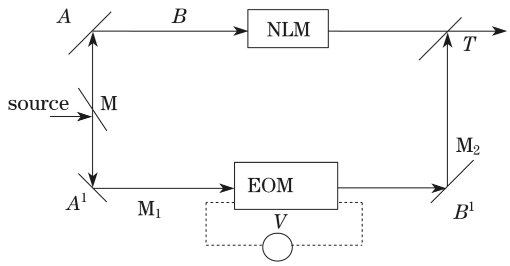

Fig. 2. Proposed modified MZI system for measurement of nonlinear correction term; dotted frame indicates the terminal for applying electrical signal.

It is already seen that, high power laser source is required in MZI to measure the nonlinear correction term. This high power CW laser signal cannot be controlled properly to go from bright to dark situations. To avoid this difficulty, a new scheme to measure the second order nonlinear correction term is proposed, as shown in Fig. 2. In this scheme, a $LiNbO_3$-based EOM of length L is kept in OA^1B^1T arm.

According to the priciple of EOM, a proper phase change of an optical signal can be made possible by applying a voltage at the c-axis of the EOM[8−10]. So, controlling the intensity of the laser source and the voltage at the EOM jointly, one can obtain the required phase difference to achieve interference pattern at the point T. For interference at T, a light signal of intensity I is used and at the same time the applied voltage at the EOM is V. Then the wave equation along the path where the NLM is kept is still

$$E_1 = E_{01}\cos\left[\omega t - k_0\left\{n_0 x_2 + (n_0' + n_1 I)x_3\right\}\right]. \quad (8)$$

The other wave, which is passing through the EOM along the path OA^1B^1T, can be represented as

$$E_2 = E_{01}\cos\left\{\omega t - k_0\left(n_0 x_1 + Ln'' - n_0^3 r_{33} V\frac{L}{2d}\right)\right\}, \quad (9)$$

where n'' is the refractive index of $LiNbO_3$ when no potential is applied. When a voltage V is applied in the electrical terminal of the EOM, the index is $n'' - n_0^3 r_{33} V \frac{1}{2d}$. r_{33} is the material constant of $LiNbO_3$, L and d are the length and width of $LiNbO_3$. So changing I and V both, the interference pattern will be obtained at the output of point T very easily. The resultant intensity of these two incoming electromagnetic waves will be I_R.

Now let I_1 be the intensity of light signal used for getting a bright fringe at the output T and V_1 be the respective voltage applied at the EOM, then certainly

$$\begin{aligned}&(n_0 x_2 + (n_0' + n_1 I_1)x_3 \\ &-n_0 x_1 - Ln'' + n_0^3 r_{33} V_1 \frac{L}{2d})k_0 \\ &= 2N\pi. \end{aligned} \quad (10)$$

For getting a dark spot at T, I_2 is the laser light intensity and V_2 is the voltage applied at EOM. Then,

$$\begin{aligned}&(n_0x_2+(n_0'+n_1I_2)x_{3.}\\&-n_0x_1-Ln''+n_0^3r_{33}V_2\frac{L}{2d})k_0\\&=(2N+1)\pi.\end{aligned} \quad (11)$$

From Eqs. (10) and (11), we can get

$$k_0\left[n_0^3\frac{1}{2}r_{33}\left(V_2-V_1\right)\frac{L}{d}+n_1\left(I_2-I_1\right)x_3\right]=\pi, \quad (12)$$

$$n_0^3\frac{1}{2}r_{33}\left(V_2-V_1\right)\frac{L}{d}+n_1\left(I_2-I_1\right)x_3=\frac{\lambda}{2}. \quad (13)$$

It is seen that changes in both the voltage $\Delta V=V_2-V_1$ and the amount of intensity $\Delta I=I_2-I_1$ are required to convert a dark spot at T to the brightest one. In the modified MZI system, if CS_2 is used as a NLM, then taking $L=1$ cm, $d=20$ μm, $r_{33}=30.8\times10^{-12}$ m/V, and the length of the NLM is 10 cm, only 2-W change of the CW laser power and 2.5-V change of electrical potential against the $LiNbO_3$ can change a dark spot at T to the brightest one. The laser power difference can be made smaller by increasing the potential difference. So, with the proper voltage at the EOM, the numerical value of the second order nonlinear correction term can be found properly by this modified MZI with a very much smaller intensity of laser light in comparison with the system excluding the $LiNbO_3$.

The proposed scheme can accommodate any suitable electro-optic material in its one arm. By using the EOM, the requirement of high intensity laser is some how compensated by voltages. Therefore with the use of considerable intensity of laser (i.e., comparatively with smaller value of intensity level), the nonlinear correction term can be found by the proposed system. The whole scheme can also be used for other applications also, e.g., the photonic logic gate, photonic data, and image processors, etc. In the above process, the loss due to reflection at the mirrors and the splitting factor of beam splitters are not considered, If those thing are considered, the expressions should be modified again.

References

1. P. Mandal, H. Bhowmic, and S. Mukhopadhyay, Opt. Eng. **45,** 075002 (2006).
2. A. J. Whang and S.-M. Chao, Opt. Rev. **10,** 346 (2003).
3. J.-J. Kao, H. -T. Wu, and C.-W. Tarn, Appl. Opt. **44,** 5422 (2005).
4. M. Dülk, St. Fisher, M. Bitter, M. Caraccia, W. Vogt, E. Gini, H. Melchior, W. Hunziker, A. Buxens, H. N. Poulson, and A. T. Clausen, Opt. Quantum Electron. **33,** 899 (2001).
5. S. Bischoff, A. Buxens, St. Fischer, M. Dülk, A. T. Clausen, H. N. Poulson, and J. Mørk, Opt. Quantum Electron. **33,** 907 (2001).
6. I. A. Bubnov, O. M. Efimov, L. B. Glebov, Y. A. Matveev, A. M. Merkryukov, V. S. Popikov, M. J. Soileau, and A. I. Stepanov, Opt. Eng. **36,** 1670 (1997).
7. D. N. Das and S. Mukhopadhyay, Appl. Opt. **37,** 8254 (1998).
8. B. J. Cusack, B. S. Sheard, D. A. Shaddock, M. B. Gray, P. K. Lam, and S. E. Whitcomb, Appl. Opt. **43,** 5079 (2004).
9. A. Shina, H. Bhowmik, P. Kuila, and S. Mukhopadhyay, Opt. Eng. **44,** 065003 (2005).
10. R. S. Quimby, *Photonics and Lasers: An Introduction* (Wiley, Hoboken, 2006) chap.9.