Optical Multiplication Using a Bisected Intersecting Waveguide

Aref Chowdhury and Leon McCaughan, *Fellow, OSA*

***Abstract*—We present an analysis of a bisected intersecting waveguide in periodically poled lithium niobate that can produce and isolate the second-order optical product $E(\omega_1 + \omega_2) \sim E_1(\omega_1)E_2(\omega_2)$ free from the near degenerate second harmonics. Model calculations of such a device fabricated in quasi-phase matched (QPM) $LiNbO_3$ predict a conversion efficiency of $\approx$1.5%/W, about 15% that of a straight waveguide of the same length, and a crosstalk of $\lesssim$−30 dB.**

***Index Terms*—Integrated optics, nonlinear optics, optical equalizers, optical frequency conversion, optical logic devices, optical mixers, optical waveguides.**

I. Introduction

THE DEPLOYMENT of fiber-optic amplifiers and the rapid development of guided-wave integrated optical circuits is making it possible to transmit more information over longer distances. It would therefore be useful to manipulate this data in the optical domain, without resorting to electrical regeneration. One important function is phase-preserving optical multiplication. Applications include optical demultiplexing via wavelength shifting, nonlinear distortion compensation, coherent detection, optical sampling and optical logic.

While the gain saturation mechanisms of a semiconductor optical amplifier (SOA) have been used to produce third-order multiplication for wavelength conversion, e.g., $E(\omega = \omega_i + \omega_j - \omega_k) \sim E_i E_J E_k^*$, the device also generates other products whose corresponding beat frequencies lie within the gain modulation bandwidth of the SOA, e.g., $\omega_i + \omega_j - \omega_k, 2\omega_i - \omega_j, 3\omega_i - 2\omega_j$, etc., (see Fig. 2 in [1]). Regarding this last point, the multiplicands (pump frequencies), themselves, are also likely to lie in the spectral vicinity of the products, further exacerbating the problem of segregating a specific product. Noncollinear four-wave mixing [2], [3] has been used to isolate one of the products, but this arrangement requires that two of the three multiplicands be made collinear, and results in a narrow detuning range ($\sim$1 GHz). In addition, SOA's have relatively large noise figures (NF $=$ $\mathrm{SNR_{in}/SNR_{out}}$ $\sim$ 15–20 dB) arising from amplified spontaneous emission (ASE) and possess a limited 3 dB bandwidth [1].

An alternate approach is sum- (or difference-) frequency multiplication. The second-order product can be easily isolated from the multiplicands, either by spectral filtering or, as we will show, by spatial discrimination. As has been demonstrated [4], third-order multiplication can be obtained from two cascaded second-order processes. Lithium niobate ($LiNbO_3$) is an ideal candidate for these processes because, in addition to its large second-order nonlinearities, the attendant optical circuitry necessary for adaptive applications such as signal processing can be monolithically integrated. Guided-wave elements such as modulators [5], switches [6], polarization rotators [7], and more recently, optical amplifiers [8] and lasers [9], [10] have been demonstrated in this substrate. Unlike the SOA, the nonlinearity in $LiNbO_3$ is active over the entire window of transparency of the material (0.35 μm to $\approx$5 μm). Also unlike the SOA, the wave mixing process is phase-preserving and, therefore, essentially noiseless [11], [12].

For signal processing applications in which the multiplicands are closely spaced in frequency, segregation of the desired optical product from other products and from the input signals must be addressed, just as in the SOA. For example, a quasi-phase matched (QPM) sum-frequency generation device for optical sampling has recently been demonstrated [13]. The sampling performance of the device is, however, limited by the second harmonics that are also generated. Thus, the effective isolation of a specific optical product in optical multiplication is of great importance. Intersecting waveguides can be made to cause two light fields to overlap and separate [14], [15]. In the following section, we describe a waveguide geometry, the bisected intersecting waveguide, fabricated in QPM $LiNbO_3$ which produces a pure second-order phase-preserving optical multiplication, $E_3(\omega_3 = \omega_1 + \omega_2) \sim E_1(\omega_1)E_2(\omega_2)$, free of near-degenerate components, $E_1^2(2\omega_1)$ and $E_2^2(2\omega_2)$.

II. Sum-Frequency Generation in Periodically Poled $LiNbO_3$

The three-wave interaction in which we are interested is sum-frequency mixing. This frequency conversion requires that a constant phase relationship be maintained among the three participating optical waves over the length of the nonlinearity. One approximate but powerful method is QPM by periodic poling [16]. The phase matching requirement for efficient sum-frequency generation, $E_3(\omega_3 = \omega_1 + \omega_2)$, from two incident optical fields, $E_1(\omega_1)$ and $E_2(\omega_2)$, propagating in a channel waveguide with a dispersive propagation constant, $\beta_i(\omega_i)$, is given by

$$\vec{\beta}_3 - \vec{\beta}_1 - \vec{\beta}_2 - \frac{2\pi m}{\Lambda}\vec{n} = 0 \tag{1}$$

where Λ is the modulation periodicity of the nonlinear susceptibility, m is the order of the grating, and $\vec{n}$ is the direction of the grating vector. From (1), the phase matching condition depends

Manuscript received August 11, 1999; revised February 1, 2000.

The authors are with the Department of Electrical and Computer Engineering, University of Wisconsin–Madison, Madison, WI 53706 USA.

Publisher Item Identifier S 0733-8724(00)03740-3.

on the propagation constants of the optical fields in the waveguide, $\beta_i(\omega_i)$, and, therefore, on the fabrication parameters of the waveguide. With the appropriate choice of waveguide parameters, the phase matching condition can be made relatively intolerant to fabrication variabilities [17], [18].

The exchange of energy among the three optical fields is governed by a set of coupled nonlinear differential equations. Neglecting loss and assuming the slowly varying envelope approximation, these reduce to (for waves propagating in the z-direction)

$$\beta_1 \frac{dE_1}{dz} = -i\mu_0 d_Q \omega_1^2 E_2^* E_3 \exp(-i\Delta\beta z) \tag{2}$$

$$\beta_2 \frac{dE_2}{dz} = -i\mu_0 d_Q \omega_2^2 E_1^* E_3 \exp(-i\Delta\beta z) \tag{3}$$

$$\beta_3 \frac{dE_3^*}{dz} = -i\mu_0 d_Q \omega_3^2 E_1^* E_2^* \exp(-i\Delta\beta z) \tag{4}$$

where $\Delta\beta = \beta_3 - \beta_1 - \beta_2 - 2\pi/\Lambda$ and d_Q is the effective second-order nonlinear coefficient for QPM interaction given by [19]

$$d_Q = \frac{2d_{ij}}{m\pi} \sin\left(\frac{m\pi}{2}\right) \tag{5}$$

Here, d_{ij} is the appropriate nonlinear coefficient (typically, $d_{ij} = d_{33} \simeq 30$ pm/V for $LiNbO_3$) and m is the order of the periodically poled grating.

If we assume undepleted multiplicands, $E_{1,2}(\omega_{1,2})$ the power at the sum-frequency is given by [20]

$$P_3(\omega_1 + \omega_2) = \eta_{\mathrm{nor}} P_1(\omega_1) P_2(\omega_2) L^2 \,\mathrm{sinc}^2\left(\frac{\Delta\beta L}{2}\right) \tag{6}$$

where L is the propagation distance in the nonlinear material and $\mathrm{sinc}(x) = \sin(x)/x$. If we consider a z-propagating channel waveguide in which the electric field is only a function of width (x) and depth (y), and assume uniform periodic reversal of the nonlinear susceptibility with a 50% duty-cycle, the normalized efficiency η_{nor} ($W^{-1}\cdot m^{-2}$) is given by (7), shown at the bottom of the page, where n_i is the refractive index at ω_i, and $E(\omega_i, x, y)$ are the modal electric field distributions. For future reference, we refer to the double integral terms outside the brackets as the overlap factor and represent it by $B(z)$.

As an example, consider two 100-mW input optical signals, centered around 1550 nm, separated by 100 GHz (≈0.8 nm) and launched into a 600-μm-long planar single-mode waveguide ($n_{\mathrm{substrate}} = 2.16$, $\Delta n = 0.005$, width $= 5\ \mu$m) in QPM ($\Delta\beta = 0$) $LiNbO_3$. Using a standard beam propagation program [21] to determine the optical overlap factor, $B(z)$, for this waveguide geometry, $\eta_{\mathrm{nor}} = 2497\%/\mathrm{W}\cdot\mathrm{cm}^2$. From (6), $P(\omega_1 + \omega_2) = 0.9$ mW. Note that, by comparison, the second-harmonic components, although not perfectly phase matched, will not be negligible, $P(2\omega_1) \simeq P(2\omega_2) \simeq 0.2$ mW.

III. The Bisected Intersecting Waveguide Device

As demonstrated above, phase-preserving multiplication of two optical signals can be performed in an optical waveguide (a two-port device), but if the two inputs are closely spaced in frequency, the output will contain the self-products (second harmonics) along with the desired cross-product [Fig. 1(a)]. Consider, instead, a pair of single mode intersecting waveguides. By properly choosing the intersection angle (2θ), the two confined input optical fields, $E_1(\omega_1)$ and $E_2(\omega_2)$, closely spaced in frequency, can be made to overlap and separate. Under conditions of proper phase matching, sum-frequency radiation (i.e., the product of the optical signals in the waveguide arms) will be generated in the overlap region. From a consideration of the transverse momentum components, $\beta_1 \sin\theta \simeq \beta_2 \sin\theta$, the sum-frequency light will radiate approximately along a line bisecting the intersecting waveguides. We, therefore, assume that at small intersection angles $(2\theta < 3^\circ)$, only the longitudinal components of the phase mismatch will contribute to $\Delta\beta z$ in (2)–(4). If we now introduce a bisecting waveguide [Fig. 1(b)] with fundamental mode propagation constant $\beta_3(\omega_1 + \omega_2)$, a sum-frequency guided wave will be excited if the following phase matching condition is met for a first-order grating:

$$\beta_3(\omega_1 + \omega_2) - \beta_1(\omega_1)\cos(\theta) - \beta_2(\omega_2)\cos(\theta) = \frac{2\pi}{\Lambda} \tag{8}$$

As we show on the following page, the large difference in the fundamental mode propagation constants between the bisecting waveguide and the intersecting arms, $\Delta\beta \simeq 0.01\ \mu\mathrm{m}^{-1}$, will effectively mismatch the coupling between them. The sum-frequency light, $E_3(\omega_3 = \omega_1 + \omega_2)$, will therefore remain in the bisecting guide while the input terms, $E_1(\omega_1)$ and $E_2(\omega_2)$, couple between their respective waveguides [waveguides A and B in Fig. 1(b)].

A linear beam propagation method (BPM) was used to minimize crosstalk in the bisecting waveguide due to the fundamentals at ω_1 and ω_2 and the second harmonics at $2\omega_1$ and $2\omega_2$, based on the input configuration shown in Fig. 1(b). For this calculation, the outer waveguides A and B are single mode and highly confining ($\Delta n = 0.005$, 5 μm width, confinement factor $\Gamma = 0.83$) for the input light at $\lambda_1 = 1550.4$ nm and $\lambda_2 = 1549.6$ nm (100-GHz separation). The bisecting waveguide C ($\Delta n = 0.01$, 3 μm width) has a propagation constant which is 0.01 $\mu\mathrm{m}^{-1}$ greater than that of the arms at 1550

$$\eta_{\mathrm{nor}} = \left(\frac{8\pi^2 d_Q^2}{n_1 n_2 n_3 c \varepsilon_o \lambda_3^2}\right) \frac{\left|\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_1(\omega_1,x,y) E_2(\omega_2,x,y) E_3(\omega_3,x,y)\,dx\,dy\right|^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_1^2(\omega_1,x,y)\,dx\,dy \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_2^2(\omega_2,x,y)\,dx\,dy \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_3^2(\omega_3,x,y)\,dx\,dy} \tag{7}$$

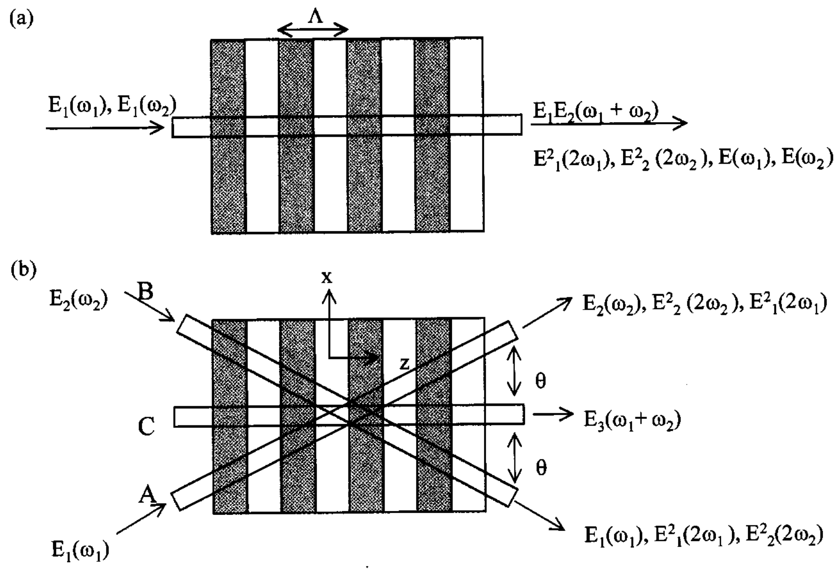

Fig. 1. Diagram of optical products generated in periodically poled $LiNbO_3$ in (a) a single waveguide and (b) in a bisected intersecting waveguide structure.

nm. Though waveguide C supports two modes at the sum-frequency, selecting the poling periodicity to phase match to the fundamental mode of the sum-frequency ensures that the energy conversion to the first-order mode is insignificant. This results because the coherence length for the first-order mode is very small compared to the length of the nonlinear interaction. Fig. 2 shows the results of a beam propagation numerical analysis of the fraction of light at frequency ω_1 launched into waveguide A that couples into waveguides B and C as a function of half-intersection angle. Local minima in the crosstalk between the input waveguide (A) and the bisecting waveguide (C) occur for the intersection angles $2\theta \approx 1.8^\circ$ ($\lesssim -30$ dB) and $\approx 3^\circ$ ($\lesssim -20$ dB). Also as seen in Fig. 2, nearly complete coupling between waveguides A and B occurs at $2\theta \approx 1.8^\circ$ [corresponding to the bar state shown in Fig. 1(b)]. We note that the "fringe pattern" which appears for $2\theta > 3.5^\circ$ in the crosstalk curve for waveguide B is due to the absorbing boundary conditions of the BPM program and to the launch conditions (the input waves are launched at an angle to the input waveguide).

Isolation of the second harmonics $E_1^2(2\omega_1)$ and $E_2^2(2\omega_2)$ from the cross-product, $E_1E_2(\omega_1+\omega_2)$ in the bisecting waveguide C, must also be considered. Fig. 3 is a plot of optical power at $2\omega_1$, launched into waveguide A, and coupled to the bisecting waveguide C. As with conventional parallel waveguide directional couplers, the propagation constant mismatch for the fundamental modes, $\beta_C(2\omega_1) - \beta_A(2\omega_1) \approx 0.03\ \mu\text{m}^{-1}$, severely limits the coupling at all angles. Note that since the second harmonic is generated continuously along waveguide A (or B), Fig. 3 represents the worst case crosstalk from the second harmonics. In short, the second harmonics (Fig. 3) show a behavior similar to their fundamentals (Fig. 2): at $2\theta \approx 1.8^\circ, E_1^2(2\omega_1)$ and $E_2^2(2\omega_2)$ have a local minima in crosstalk ($\lesssim -30$ dB) between the intersecting guides A and B and the bisecting waveguide C. It is equally important that the sum-frequency light $E_1E_2(\omega_1+\omega_2)$ excited in the bisecting waveguide not couple to either

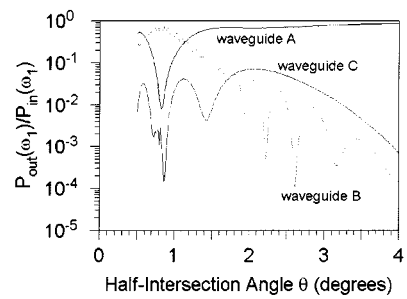

Fig. 2. Fraction of light at ω_1 (or ω_2) coupled among the waveguides as a function θ, half the intersection angle. Input light, $E_1(\omega_1)$ (or $E_2(\omega_2)$), is launched into waveguide A (or B) (see Fig. 1).

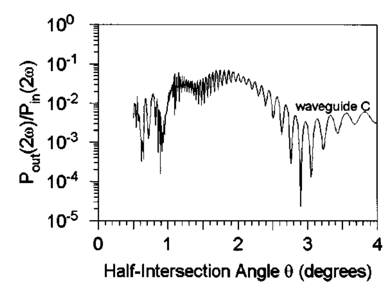

Fig. 3. Fraction of second harmonic light $2\omega_1$ (or $2\omega_2$) coupled between waveguides A (or B) and C (Fig. 1) as a function of θ, half the intersection angle.

input waveguide arm. BPM calculations (not shown) at the sum-frequency, $\omega_1 + \omega_2$, reveal that, because of the propagation constant mismatch, coupling from waveguide C to waveguides A and B is also negligible.

Finally, we have estimated the sum-frequency conversion efficiency of our device using a BPM to numerically determine the overlap factor, $B(z_i)$, at 50-μm intervals (Fig. 4). The bisected intersecting waveguide geometry is as given above with intersection angle $2\theta = 1.8^\circ$. Assuming undepleted input signals

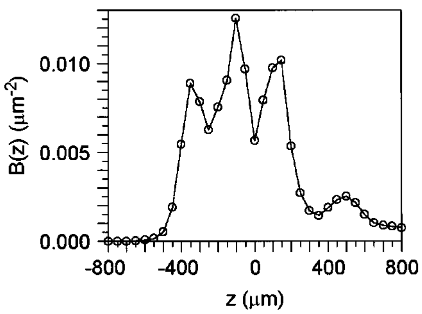

Fig. 4. Plot of the overlap integral, $B(z_i)$, for the bisected intersecting waveguide, evaluated every 50 μm. The center of the device is located at $z = 0$.

and QPM, the expression for the sum-frequency output power given by (6) can be approximated as

$$P(\omega_1+\omega_2) \approx \left(\frac{8\pi^2 d_Q^2}{n_1 n_2 n_3 c\varepsilon_o \lambda_3^2}\right) P(\omega_1)P(\omega_2) \times \left[\sum_i \sqrt{B(z_i)}\Delta z_i\right]^2. \quad (9)$$

From Fig. 4 and (9), two 100-mW input optical signals at 1550.4 nm and 1549.6 nm (100-GHz separation), will produce ≈ 0.15 mW in waveguide C at the sum-frequency. We can see from Fig. 4 that significant mode overlap occurs for a length ≈ 600 μm while the physical overlap of the waveguides is only 512 μm. Taking 600 μm as the effective length of the device, we ascribe to the bisected intersecting waveguide an average normalized conversion efficiency of $\bar{\eta}_{\rm nor} = 415\%/\text{W}\cdot\text{cm}^2$ or equivalently in terms of the device efficiency, $\eta_{\rm dev} = 1.5\%/\text{W}$. By comparison, a QPM 600 μm long straight waveguide, comparably excited, will produce (see Section II) 0.9 mW sum-frequency output, corresponding to 2500%/W·cm^2. From these first-order calculations, it can be seen that the bisected intersecting waveguide is able to form and segregate the second-order optical product $E_3(\omega_3 = \omega_1+\omega_2) \sim E_1(\omega_1)E_2(\omega_2)$ from two separate inputs, with moderate efficiency. We note that a straight waveguide can be fabricated several centimeters in length, whereas the bisected intersecting waveguide is limited to a length of 600 μm for $2\theta = 1.8^\circ$; however, the increased conversion efficiency in the straight waveguide will be achieved at the expense of the lack of ability to segregate the second-order sum-frequency product from the second harmonics and unconverted input fields. We also note that the overall efficiency will be reduced by the presence of waveguide propagation losses. Typical channel waveguide losses are $\sim$0.2 dB/cm or less at the input wavelengths ($\lambda = 1.5$ μm) [22] and $\sim$1.3 dB/cm at the sum-frequency (i.e., the center waveguide) [23]. Over the 600 μm active length of the device, these losses are negligible.

The third-order products needed for applications such as wavelength shifting and nonlinear distortion compensation in fiber systems can be obtained by cascading two of these devices. This idea of cascading second-order processes has been previously demonstrated [24], [25]. The second-order output from the first bisected intersecting waveguide device, together

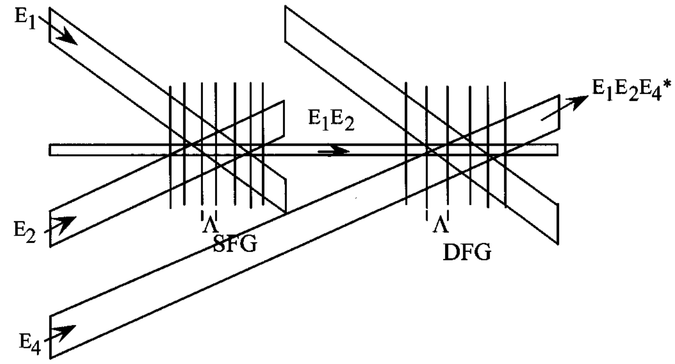

Fig. 5. Third-order multiplier formed from cascading two bisected intersecting waveguides.

with a third input $E_4(\omega_4)$, is now coupled into a second bisected intersecting waveguide device, this time phase matched to produce difference-frequency mixing. Fig. 5 is a representation of such a cascaded pair of bisected intersecting waveguides which would convert three input optical signals, $E_1(\omega_1)$, $E_2(\omega_2)$, and $E_4(\omega_4)$, to the product $E_{\rm out}(\omega_1+\omega_2-\omega_4) \sim E_1E_2E_4^*$, free of any other third-order products (which appear in SOA's).

If we assume, as shown earlier, an efficiency of 1.5%/W for both devices in Fig. 5, then three 100-mW input signals will produce a third-order output of ≈ 225 nW. Clearly, improvements in the efficiency of the bisected intersecting waveguide device and amplification of the second- and/or third-order products must be examined for a practical three-term multiplier. Adiabatic tapering can be used to reduce the waveguide cross section [26], which will increase the conversion efficiency. It should also be possible to simply use more highly confining waveguides than demonstrated here. The poling periodicity guarantees that the sum-frequency, difference-frequency, or second-harmonic conversions are mode-selective. Care would need to be taken to ensure that subsequent mode conversion does not take place.

IV. Summary

We have presented and numerically analyzed a bisected intersecting waveguide geometry in periodically poled lithium niobate. The device can perform second-order optical multiplication. By properly choosing the intersection angle (which is 1.8° for the device studied), the bisected intersecting waveguide has the distinct advantage of not only producing a second-order product but also spatially isolating it from the second harmonics and unconverted input signals. Applications include optical logic, coherent detection, and optical sampling. Numerical analysis indicates that the device has an average normalized conversion efficiency of 415%/W·cm^2 or equivalently a device efficiency of 1.5%/W. By using two 100-mW inputs separated by 100 GHz and centered around 1550 nm, the power of the second-order optical product is $P(\omega_1+\omega_2) \approx 0.15$ mW. The crosstalk was calculated to be lower than -30 dB. Cascading two of these devices produces third-order multiplication (also free of its near-degenerate components), which has important applications in wavelength conversion and nonlinear distortion compensation.

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Aref Chowdhury received the B.E. degree from the Honors College at the State University of New York at Stony Brook in 1994, with a double major in electrical engineering and applied mathematics and statistics. He is currently pursuing the Ph.D. degree at the University of Wisconsin-Madison.

From 1995 to 1997, he worked as a Senior Engineer for ALCATEL CIT. His responsibilities included testing, commissioning, operation and maintenance of ALCATEL switching systems in Bangladesh. His research interests are in the areas of nonlinear optics and fiber optic communication.

Mr. Chowdhury is a Grumman Corporation Scholar and a member of Tau Beta Pi, Eta Kappa Nu and Sigma Xi.

Leon McCaughan received the Ph.D. degree from the University of Michigan, Ann Arbor.

From 1979 to 1980, he held a Postdoctoral appointment with Brookhaven National Laboratory. From 1980 to 1984, he was with Bell Laboratories, where he was engaged in the research and development of integrated optic devices. He is currently a Professor in the Department of Electrical and Computer Engineering at the University of Wisconsin–Madison. His research includes guided wave integrated optics, nonlinear optics and fiber optics.

Dr. McCaughan is a Fellow of the Optical Society of America (OSA).