Optical Properties of Polymer Waveguides Dispensed on an Erbium/Ytterbium Codoped Glass

Madhu Krishnaswamy, David Boertjes, J. N. McMullin, and Barrie P. Keyworth, *Member, IEEE*

***Abstract*—A composite waveguide was fabricated by dispensing polymer on top of an erbium/ytterbium codoped bulk glass. The parabolic surface of the polymer layer induces a transverse graded index waveguide behavior enabling tighter lateral confinement of light than in a typical step-index multimode waveguide. Spontaneous emission of light in the 1520–1570-nm band has been observed. We have also observed up to 1.7-dB enhancement of transmitted signal with 210 mW of launched 975-nm pump light in a waveguide 1.0-cm long.**

I. Introduction

ERBIUM-DOPED planar optical waveguide amplifiers (Er-POWA) operating in the 1550-nm wavelength window are expected to play a prominent role in integrated optical circuits. Applications may include telephony, CATV services, etc. High concentrations of erbium are required to provide net signal gain over a few centimeters since the length of the Er-POWA is usually limited by the size of the underlying substrate. The importance of the chemical composition of the host glass has been well documented [1]. Optimizing the glass composition continues to be an active area of research. A variety of codopants such as ytterbium, phosphorous, and aluminum have been attempted to improve the solubility of the erbium oxide. Erbium-doped glass films deposited by plasma enhanced chemical vapor deposition (PECVD), flame hydrolysis (FHD) and RF sputtering have produced short-length amplifiers on silicon substrates [2]–[4]. The amount of erbium ions that can be incorporated into silica using FHD and PECVD is typically limited to less than 1 w.t.%. Hence, the optimum amplifier length is in the order of tens of centimeters. This requires the use of bent waveguides to fit the amplifier in a small substrate [3]. Gain has also been reported in ion-exchanged waveguide amplifiers, including one integrated with a planar lossless splitter [5], [6]. Since RF sputtering and ion-exchanged processes make use of a bulk glass, the host composition can be tailored to accept high erbium concentrations, high enough to produce significant signal gain in straight ridge/channel waveguides which are less than 5-cm long.

Previously, we investigated ridge waveguides made of sputtered Er-doped glass films. However, difficulties were encountered in maintaining the spectroscopic properties of the bulk glass during sputtering. Short fluorescence lifetimes were observed in the resulting sputtered films. Further processing of these films through conventional wet and dry etching techniques resulted in waveguides that were lossy. A search for alternative waveguide structures was initiated with the aim of simplifying the fabrication. Recently, we observed low loss and spontaneous and stimulated emission in a composite strip-loaded Er-doped waveguide where lateral confinement was achieved through a layer independent of the chemically complex erbium-doped glass [7]. However, the problem of short fluorescence lifetimes in the sputtered films remained.

In this paper, we report stimulated emission in an evanescently pumped polymer waveguide formed on an Er-doped bulk glass substrate. Polymer waveguides are attractive because of their low loss, low cost and ease of fabrication. Typically, they have been used as multimode (MM) step-index structures for optical interconnects in hybrid integrated circuits [8]. Recently, graded-index MM polymer waveguides [9], [10] and a planar, graded effective index MM polymer waveguide [11] have been reported. In the latter, which are formed by a simple dispensing technique, the parabolic surface of the polymer was found to produce a near-quadratic index waveguide, thus confining light within a region narrower than the overall waveguide dimension. Conceivably, such waveguides may be formed over long distances (0.5 m) and may be important in reducing dispersion in multi-gigabit/s data buses. This type of waveguide was used in this study.

In Section II, the steps involved in the fabrication are described. Theoretical passive optical properties and experimental active optical properties of the composite waveguide are presented in Sections III and IV, respectively. Concluding remarks follow in Section V.

II. Fabrication

For these experiments, we used an erbium/ytterbium codoped phosphate bulk glass ($n = 1.53$), which is commercially available (Kigre QX/Er [12]). The precise dopant levels are unavailable but the erbium content is known to be in the range 0.1–0.2 w.t.% and the ytterbium content approximately a factor of 15 higher. A 1" $\times$ 1" $\times$ 2 cm transmission sample of the QX/Er was sliced to a 2-mm thick piece. Both top and bottom surfaces of this glass were polished to optical standards. Using a pressurized syringe under computer control [13], a UV-curable polymer optical adhesive (NOA 81 [14]) with a refractive index of 1.56 was dispensed directly on the erbium-doped glass. The polymer was cured by a UV source that was trailing the dispensing syringe by a few millimeters. The resulting parabolic polymer waveguide had a maximum height of 8 μm and a base width

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The authors are with Telecommunications Research Laboratories, Edmonton, AB T5K 2P7 Canada. They are also with the Department of Electrical Engineering, University of Alberta, Edmonton, AB T6G 2G7 Canada.

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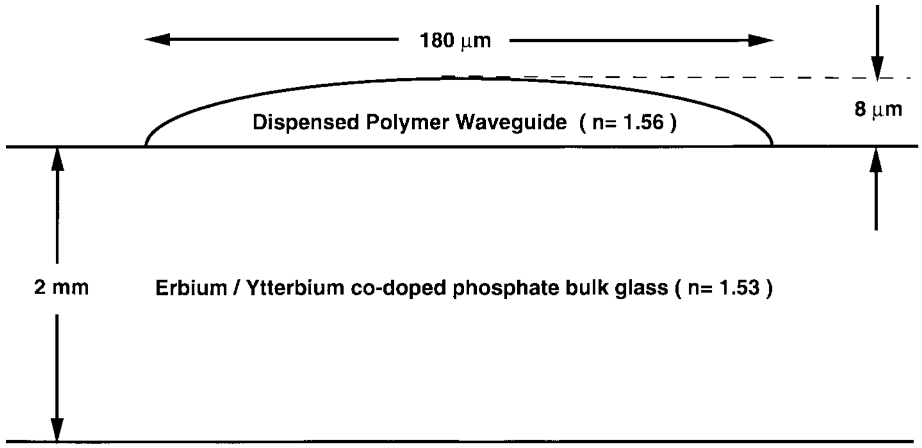

Fig. 1. Cross section of dispensed polymer waveguide on the Er/Yb codoped bulk glass. The refractive indices are quoted for $\lambda = 632$ nm. The fabricated waveguides were 1.0-cm long.

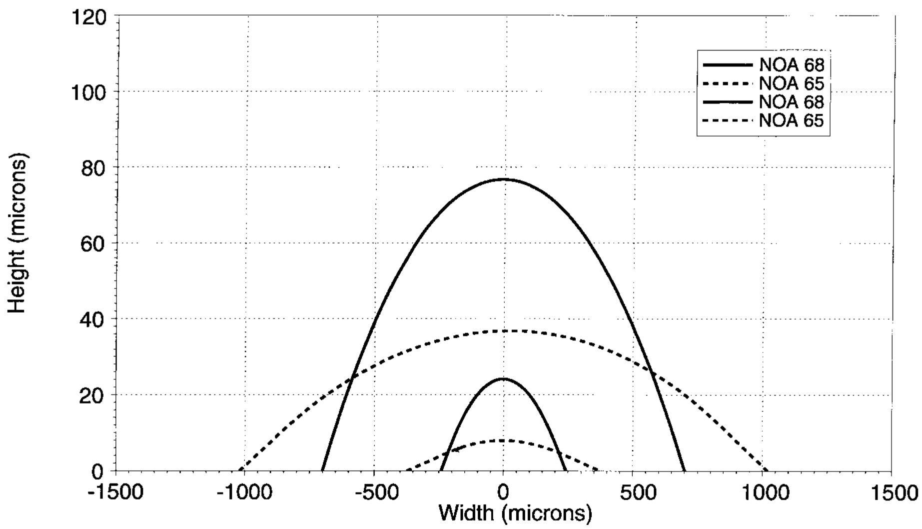

Fig. 2. Profilometer scans of two different polymers dispensed on an SiO_2 substrate. The aspect ratio of each type of polymer is relatively constant over a wide range of waveguide sizes.

of 180 μm (Fig. 1). Input and output facets were obtained by scribing and cleaving the glass substrate and the resulting waveguides were 1-cm long.

The aspect ratio of a waveguide formed by this method is determined by the contact angle at the edge, which is a function of the surface tensions at the liquid/air and liquid/glass interfaces. As shown in Fig. 2, each polymer/substrate combination has a relatively constant aspect ratio over a wide range of waveguide dimensions. The process is very repeatable. For example, in an array of 100 microlenses formed by this technique, the standard deviation in focal length was found to be approximately 1% [15].

III. Passive Optical Properties

Several passive optical properties of these waveguides are of interest, in particular, the number of vertical modes, the shape and size of the fundamental mode, the coupling efficiency to a single-mode fiber, the amount of mode in the substrate, and the overlap between the 980-nm pump and the 1550 nm signal mode in the erbium/ytterbium glass. The number of modes supported by the waveguide was obtained by using calculations for a slab waveguide of height 8 μm. This predicts five and three modes for wavelengths of 980 and 1550 nm, respectively. The slab becomes single-moded for both wavelengths at a height of approximately 2 μm.

The coupling between the waveguide and the single-mode fiber depends on the overlap of the modes in both structures. The mode in the fiber is assumed to be a Gaussian defined uniquely by the mode field diameter (MFD) at each wavelength. The MFD can be calculated from the wavelength of the light, the indices of the core and cladding, and the core diameter. The result is 5.8 and 10.0 μm for wavelengths of 980 and 1550 nm, respectively, for the fiber used in the experiment.

Calculating the mode shape for the waveguide is slightly more complicated. There are two different cases to be considered, one in each of the x (horizontal) and y (vertical) directions. We will make the assumption that the mode is sufficiently confined in the x direction such that the height of the waveguide does not change significantly in the region of the mode and that the two directions can then be separated.

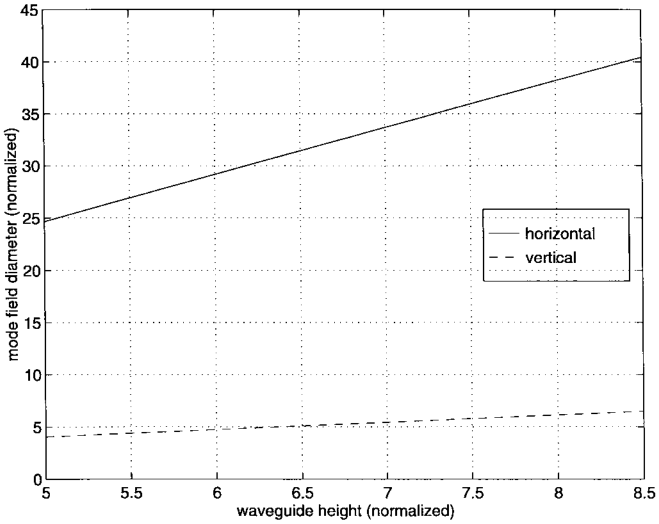

Fig. 3. Normalized mode field diameter versus normalized waveguide height, where the height:width ratio of the waveguide has been kept constant.

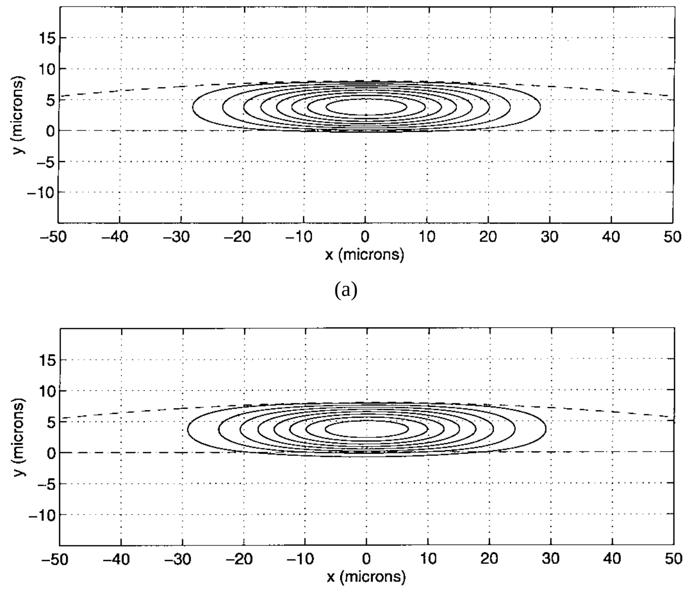

Fig. 4. 2-D profile of the fundamental mode for: (a) $\lambda = 980$ nm and (b) $\lambda = 1550$ nm in a waveguide 8 μm high and 180 μm wide.

In the y direction the mode is given by the solution of the simple slab waveguide. The horizontal direction displays a graded index effect which is most easily seen by using the effective index method in calculating the vertical slab mode. As the height of the waveguide decreases, so does the effective index of the slab mode. A parabolic graded index waveguide has solutions which are the Gauss–Hermite modes. The first of these modes is a simple Gaussian and will be the only one with which we will be concerned. The width of this mode can be calculated from the profile of the waveguide. Fig. 3 shows the effect of changing the height of a waveguide while maintaining a constant height:width ratio of 1:22.5 (the same as the fabricated waveguide) on the vertical and horizontal MFD's. Both axes of the figure are normalized to the wavelength of the light being used. Using the MFD's from Fig. 2 and the fiber MFD's, the coupling efficiency was estimated to be 0.53 and 0.56 at 980 and 1550 nm, respectively. The shape of the fundamental mode for both wavelengths of interest is shown in Fig. 4. The percentage of the fundamental pump and signal mode that overlaps with the erbium/ytterbium glass is 0.21 and 0.74, respectively.

The overlap between the pump and signal modes within the erbium/ytterbium glass is also an important factor. Weak overlap results in stronger absorption of the signal than the pump, thus increasing total losses while reducing the opportunity for stimulated emission. In the substrate, the form of both slab modes is a decaying exponential. The major difference between them is the shape in the x direction as determined by the graded effective index and consequently this overlap is high, 0.97 for this waveguide.

IV. Active Optical Properties

The active properties of the waveguide were studied using a tunable Ti : Sapphire laser. The Ti : Sapphire crystal was pumped from opposite ends with two 5-W argon lasers. The output from the Ti : Sapphire was combined with a signal from a 1550-nm laser diode in a fiber WDM. The output pigtail of the WDM was butt-coupled to the input facet of the composite polymer/glass waveguide. A multimode fiber was used at the output facet of the waveguide to gather light which was then filtered using a monochromator and subsequently detected. The spontaneous emission spectrum in the 1520–1570-nm wavelength region with 210 mW of launched 975-nm pump power is shown in Fig. 5. The peak emission is near 1535 nm. Bright green light was visible throughout the length of the waveguide, indicating that up-conversion processes were occurring. This is most likely a consequence of the high ytterbium concentration. The intensity of the green light did not diminish when the Ti : Sapphire was tuned to wavelengths between 900 and 1000 nm, which corresponds to the wide absorption band of ytterbium. A fluorescence lifetime of 8 ms was observed in this waveguide with 210 mW of launched pump power (Fig. 6). It should be noted that the evanescent pump intensity in the erbium/ytterbium glass is not high enough to significantly quench the lifetime.

Fiber-to-fiber losses were measured at three wavelengths to separate the insertion losses from the losses due to the erbium. The throughput loss was 4.2 dB @ 1300 nm, 5.8 dB @ 1550 nm, and 4.5 dB @ 975 nm. Since neither erbium nor ytterbium has an absorption band near 1300 nm, the losses at that wavelength can be attributed to coupling losses at the two end-facets and the losses inherent in the polymer waveguide. The coupling loss was probably higher than the 3 dB estimated in the last section since the cleaved end facets were seen to be tilted at several degrees from the ideal orientation. The on-chip erbium-induced loss was approximately estimated to be 1.6 dB @ 1550 nm and 0.3 dB @ 975 nm.

The enhancement of a transmitted signal at a wavelength of 1550 nm was studied. The 1550-nm laser diode was modulated at a frequency of 2 kHz so that amplified spontaneous emission could be ignored during the pump probe measurements. The attenuation of the signal was found to decrease as much as

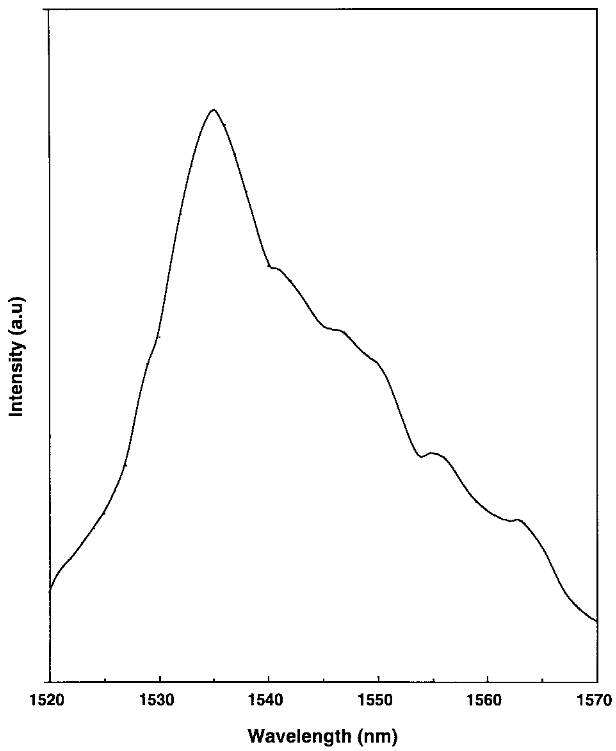

Fig. 5. Spontaneous emission spectrum in the composite polymer/glass waveguide. The pump is 210 mW launched from a Ti : Sapphire laser.

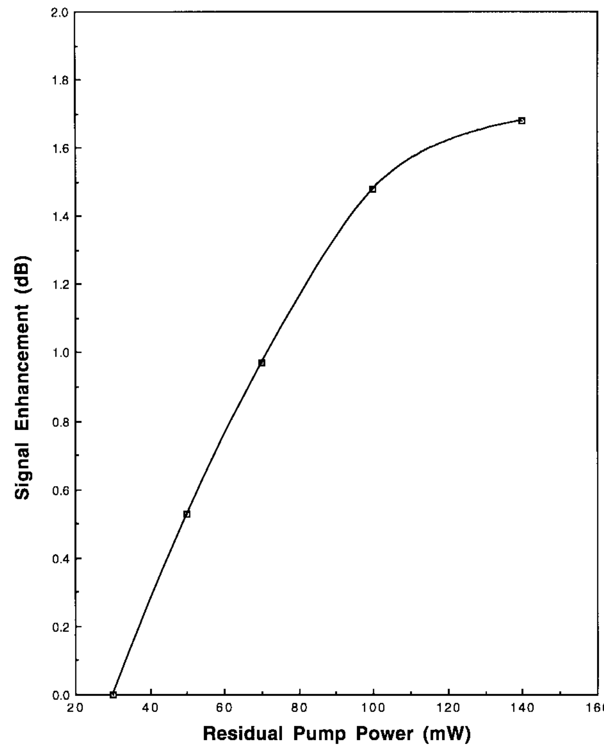

Fig. 7. Transmitted 1550-nm signal enhancement as a function of residual 975-nm pump power. The launched signal power is − 20 dBm.

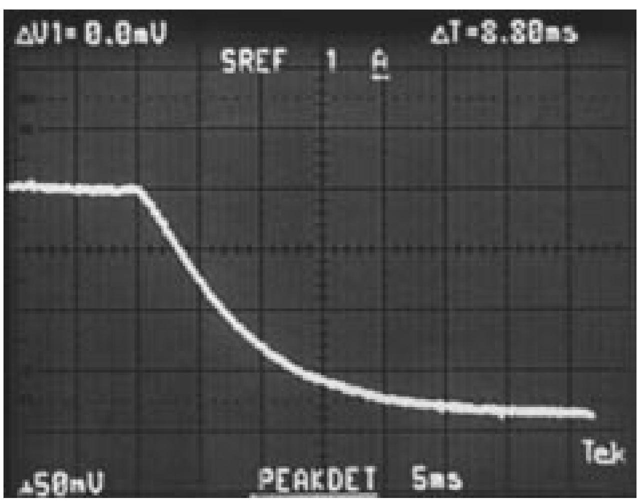

Fig. 6. Fluorescence lifetime (time taken for the intensity to decay to $1/e$ of its peak value) in the composite polymer/glass waveguide.

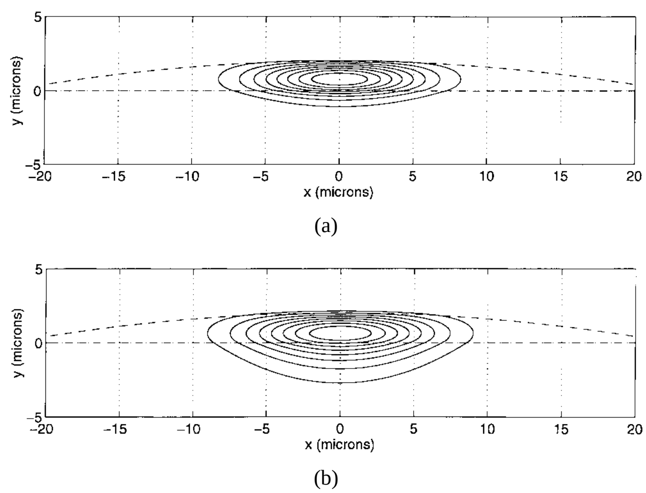

Fig. 8. 2-D profile of the fundamental mode for: (a) $\lambda = 980$ nm and (b) $\lambda = 1550$ nm in a waveguide 2 μm high and 45 μm wide.

1.7 dB when pumped with an estimated 210 mW. The relationship between transmitted signal enhancement and residual pump power exiting the waveguide is shown in Fig. 7. The saturation at high pump power suggests that the maximum signal enhancement was obtained for this device.

V. Discussion and Conclusion

Dispensed polymer waveguides on glasses with low-erbium concentrations have the potential to be used as amplifiers. In composite waveguides of this kind, where evanescent fields are used to excite the erbium ions, weak overlap of the fundamental transverse pump mode with the active region is inevitable. Hence, the total pump power required to attain threshold pump intensity and sustain population inversion in the active region will be high. It is therefore advisable to work with low erbium concentrations in such devices. Although the gain coefficients and efficiencies of these evanescently-pumped waveguides will not rival those of planar waveguides with tight mode-field confinement, the ease of fabrication may be an attractive tradeoff.

It should be noted that the waveguide used in the experiment is not optimal. Assuming the same refractive indices as in Fig. 1, if the dimensions of the polymer layer were reduced to 2 μm × 45 μm, a much higher fraction of the modes propagate in the gain region while maintaining comparable coupling and mode overlap. The overlap between the fundamental pump and signal modes within the active region reduces only slightly from 0.97 to 0.93. However, the percentages of pump and signal light propagating in the active region increase to 8.3 and 25, respectively (Fig. 8). With more of the pump now propagating in the active region, the optimum waveguide length (to maximize signal enhancement) will be longer. Work is proceeding to develop longer dispensed polymer waveguides with optimized cross sections.

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Madhu Krishnaswamy received the B.Sc. degree in electrical engineering from the University of Alberta in Edmonton, AB, Canada, in 1993, and is currently working toward the Ph.D degree at the University of Alberta.

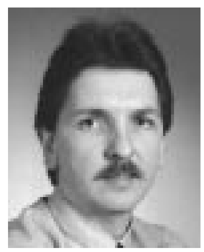
His dissertation is on numerical modeling and fabrication of erbium-doped waveguide devices and fabrication of hollow glass microchannels on silica.

David W. Boertjes received the B.Sc. degree (honors) in physics from the University of New Brunswick, Fredericton, NB, Canada, in 1993 and the M.Sc. degree in physics from Dalhousie University, Halifax, NS, Canada, in 1995, and is working toward the Ph.D. degree in electrical engineering at the University of Alberta in Edmonton, AB, Canada.

His work at Dalhousie was in the field of nonlinear optics.

J. N. McMullin was born in Montreal, PQ, Canada, in 1947. He received the B.Sc (honors) degree in physics from McGill University, Montreal, PQ, Canada, in 1968, and the Ph.D degree in astrophysics from the University of Rochester, Rochester, NY, in 1975.

From 1975 to 1983, he worked in the area of controlled fusion, and since 1983, he has been a faculty member in the Department of Electrical Engineering at the University of Alberta, Edmonton, AB, Canada, in optical communications. His current interests are modeling and hybrid integration in integrated optics and diffractive optics.



Barrie P. Keyworth (M'96) received the B.Eng. degree in electrical engineering from the Technical University of Nova Scotia, Halifax, NS, Canada, in 1986. From 1986 to 1991, he was involved in a joint research venture between the Technical University of Nova Scotia and Bell-Northern Research Limited which led to the M.A.Sc. and Ph.D. degrees.

From March 1991 to September 1996, he was a member of the Photonics Research group at Telecommunications Research Laboratories (TRLabs). During this period he held a number of positions including Photonics Research Scientist, Photonics Program Manager, and Acting Director. He was also a member of the Canadian Institute for Telecommunications Research and an Adjunct Professor in the Electrical Engineering Department at the University of Alberta, Edmonton, AB, Canada. While at TRLabs, he was involved in a number of projects including the design and analysis of novel optoelectronic devices for use in broadband switching applications, development of monolithic and hybrid integration technologies, free-space and guided-wave optical interconnects, and rare-earth doped waveguide amplifiers. During the time he was involved in the joint venture between the Technical University of Nova Scotia and Bell-Northern Research Limited, he published numerous technical papers on all-optical and electro-optical switching. He has contributed to more than 35 technical publications and one patent. He was recipient of several awards including a Natural Sciences and Engineering Research Council (NSERC) Postgraduate Scholarship and a scholarship to attend the 1990 NATO Advanced Study Institute in Glasgow, Scotland. He recently joined JDS Fitel Inc., Ottawa, Canada, as Manager, Components Research.

Dr. Keyworth is a member of SPIE and LEOS.