Influence of Scattering and Two-Photon Absorption on the Optical Loss in GaAs–Al_2O_3 Nonlinear Waveguides Measured Using Femtosecond Pulses

Soma Venugopal Rao, Konstantinos Moutzouris, Majid Ebrahimzadeh, Alfredo De Rossi, G. Gintz, Michel Calligaro, Valentin Ortiz, and Vincent Berger

***Abstract*—The influence of scattering and two-photon absorption on the optical loss in GaAs–Al_2O_3 semiconductor nonlinear waveguides has been studied using femtosecond pulses. By deploying a scattering technique, loss coefficients were evaluated over an extended wavelength range of 1.3–2.1 μm in the near-infrared. A systematic study involving intensity and wavelength dependence of the loss revealed the presence of two-photon absorption for wavelengths below 1.6 μm. A simple nonlinear transmission study enabled the separation of the two-photon absorption coefficient from scattering and linear absorption. The calculated two-photon absorption coefficients were $\sim$9–20 cm/GW.**

***Index Terms*—Nonlinear frequency conversion, optical losses, scattering technique, semiconductor waveguides, two-photon absorption.**

I. INTRODUCTION

RECENT advances in the material research of III-V semiconductor nonlinear waveguides continue to pave the way for development of a new generation of integrated photonic devices for a variety of applications ranging from wavelength mixing for telecommunications to infrared (IR) frequency conversion for spectroscopy and trace gas detection. Measurement of optical loss represents a vital component in the assessment of these waveguides for nonlinear frequency conversion in the near- and mid-IR. Accurate knowledge of this parameter is particularly important in the performance evaluation and implementation of resonant devices, most notably integrated optical parametric oscillators (OPOs) where, due to the small available nonlinear gains, the magnitude of loss can have a dramatic impact on the oscillation threshold. In single-pass devices, such as nonlinear frequency shifters, wavelength mixers [1], and harmonic generators [2], [3], optical loss is also vitally important since it clearly sets an upper limit to the maximum output power and conversion efficiency that may be achieved in the nonlinear process.

Unlike in their organic and inorganic counterparts, losses in semiconductor nonlinear waveguides are more difficult to characterize due to the inaccurate knowledge of effective refractive indices and facet reflectivities. Over the past few years, several techniques including the cutback method [4], prism coupling [5], [6], photo-thermal deflection [7], and the Fabry–Perot (FP) interference method [8]–[11], have been employed for the evaluation of loss. Other techniques including intensity modulation using an acousto-optic modulator [12], photo-luminescence [13], optimized end-fire coupling [14], self-pumped phase conjugation [15], scattering technique [16], multisection single-pass technique [17], and several others [18]–[22] have all been tried and tested. While most of these techniques are suited for the assessment of waveguides with losses greater than 1 dB/cm, many are not universally appealing due either to their complexity (e.g., self-pumped phase conjugation method) or destructive nature (e.g., cut back method). Some techniques such as the prism-coupling technique are not applicable to semiconductor waveguides, since the prisms have to be in contact with the waveguide, which is neither practical nor desirable. The FP interference technique has proved to be the most favorable and successful approach for evaluation of losses below 1 dB/cm, including in complex structures such as directional couplers, Y-junctions, and photonic crystal waveguides [23]–[25]. However, even though the technique is simple, robust, and nondestructive, it has a number of drawbacks including stringent frequency-stability requirements of the optical source, accurate knowledge of facet reflectivities, and precision in the facet parallelism of the waveguide etalon for correct analysis of the obtained data [26], [27]. The scattering technique, on the other hand, is a relatively uncomplicated method without particularly stringent demands on the optical source and has been successfully demonstrated in a variety of optical waveguides [28]–[32]. Moreover, for any waveguide application in telecommunications involving wavelength-division multiplexing (WDM) [either dense WDM or time-division multiplexing (TDM)], it is imperative to use femtosecond pulses utilizing their large bandwidth. In such cases, the continuous-wave (CW) FP technique would not provide any additional information regarding the propagation and interaction of femtosecond pulses within the nonlinear medium. On the contrary, the scattering technique using femtosecond pulses provides this vital information, which makes this method even even more attractive for such applications.

It has been well established that the scattering technique is a practical method for measuring losses, especially in the 0.3–3.0 cm^{-1} range [28]–[32]. The majority of loss measurements using this method, and as well as other techniques, have

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S. V. Rao, K. Moutzouris, and M. Ebrahimzadeh are with the School of Physics and Astronomy, University of St. Andrews, North Haugh, Fife KY16 9SS, Scotland, U.K. (e-mail: vrs2@st-and.ac.uk; me@st-and.ac.uk).

A. De Rossi, G. Gintz, M. Calligaro, V. Ortiz, and V. Berger are with the THALES Research and Technology, 91400 Orsay, France.

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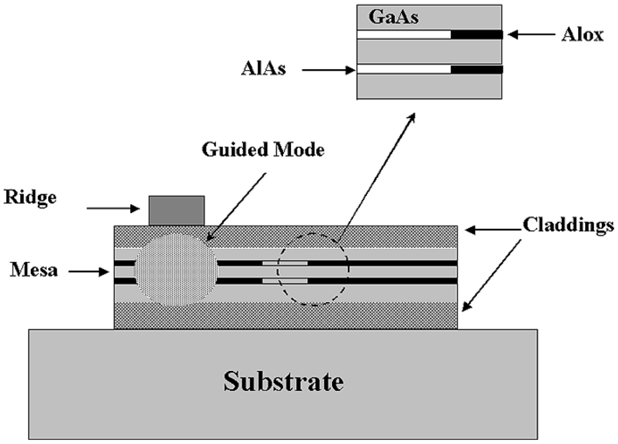
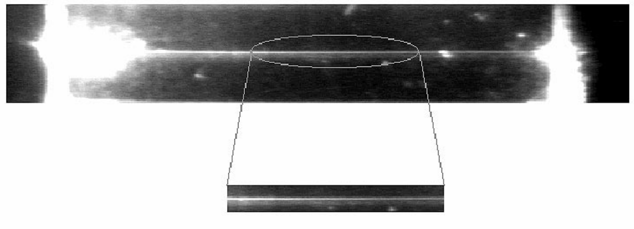


Fig. 1. Structure of sample used for loss measurements. Specific details are provided in the text.

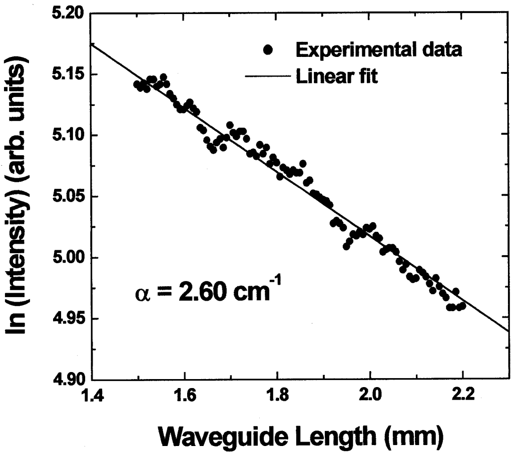
to date been performed at discrete wavelengths in the near-IR using a variety of optical sources. Recently, we reported our initial measurements of optical loss in GaAs–Al_2O_3 semiconductor nonlinear waveguides over an extended wavelength range from 1.3 to 2.1 μm in the near-IR using the femtosecond scattering technique by employing a tunable OPO. By using femtosecond pulses from this OPO and by performing a systematic and detailed study at different input intensities, we have determined the contributions of scattering and two-photon absorption to the total loss observed over an extended wavelength range in the infrared, including the important telecommunications window. The results of these measurements are significant in the context of nonlinear frequency conversion experiments in the near-IR, including difference frequency generation [1], second-harmonic generation (SHG) [2], [3] and optical parametric fluorescence [33], [34] that have recently been successfully demonstrated in such waveguides.

II. EXPERIMENT

The complete details of the experimental set up have been described previously [35]. We utilized the wavelength versatility of femtosecond pulses derived from a periodically poled lithium niobate (PPLN) OPO pumped by a Ti:sapphire laser. The pulse duration was measured to be ~250 fs in the wavelength regions close to 1.5 μm and ~200 fs near 2.0 μm, and the pulse repetition rate was ~90 MHz. All measurements were performed with TE-polarized input pulses. In the scattering technique, we expect the intensity of the light scattered normal to the waveguide at a given point along the propagation direction to be proportional to the intensity of the light in the waveguide at that point. The loss coefficient can then be determined by mapping the decay of scattered light intensity along the propagation length of the guide. This decay follows an exponential dependence according to $I_L = I_0 e^{-\alpha L}$, where I_L is the scattered intensity after a propagation length L through the waveguide, I_0 is the initial intensity at the start of the path, and α is the overall loss coefficient to be determined. The presence of any defects and inhomogeneities in the propagation path would only affect the uniformity of the exponential decay. The above equation can be rewritten in the form $\ln(I_L) = \ln(I_0) - \alpha L$. Therefore, by recording the scattered intensity along the waveguide and using a suitable algorithm based on the above equation, we can readily determine the overall loss coefficient α. In the present study the scattered intensity was monitored by an IR camera (Electrophysics, Micron Viewer 7290A) sensitive in the 0.4–2.2-μm spectral ranges. The sample structure, shown in Fig. 1, was similar to that used in the SHG experiment [2]. It consisted of (GaAs $\langle 001 \rangle$ substrate)/1000 nm AlAs/1000 nm $Al_{0.7}Ga_{0.3}As$/4 X (37 nm AlAs/273 nm GaAs)/37 nm AlAs/ 1000 nm $Al_{0.7}Ga_{0.3}As$/30 nm GaAs. We used a 3.5-mm long sample that incorporated several waveguides of different widths ranging from 2 to 6 μm. This is a passive device and, therefore, semiconductor alloys are chosen such that the material is transparent at the operating wavelengths.



(a)

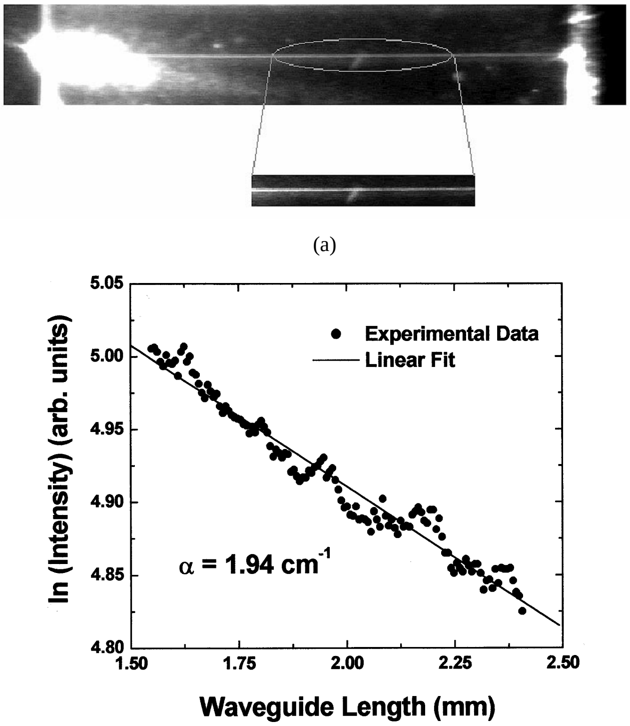


(b)

Fig. 2. (a) Photograph of a typical image of scattered light in the waveguide at 1.5 μm. Light is coupled into the waveguide at the left-hand side. Magnified image of the area is selected for loss evaluation. (b) Intensity profile of the scattered light inside the waveguide at 1.5 μm with a loss of 2.6 cm^{-1}.

III. RESULTS AND DISCUSSION

Figs. 2(a) and 3(a) show typical scattering profiles in the waveguide at wavelengths of 1.5 and 2.0 μm, respectively. The intense profiles observed at the input and output extremes correspond to the coupling losses at facets of the waveguide. Other isolated areas of discontinuous intensity are due to the scattering from either dust particles or defects. The clear streak is the scattered light while propagating through the waveguide. A small change in the waveguide position or misalignment of the input beam resulted in the disappearance of the streak, confirming that it corresponded to the guided propagation mode only. Measurements of loss were, therefore, conducted over this



(a)

(b)

Fig. 3. (a) Photograph of a typical image of scattered light in the waveguide at 2.0 μm. (b) Intensity profile of the scattered light for a 1.94-cm^{-1} loss waveguide at 2.0 μm.

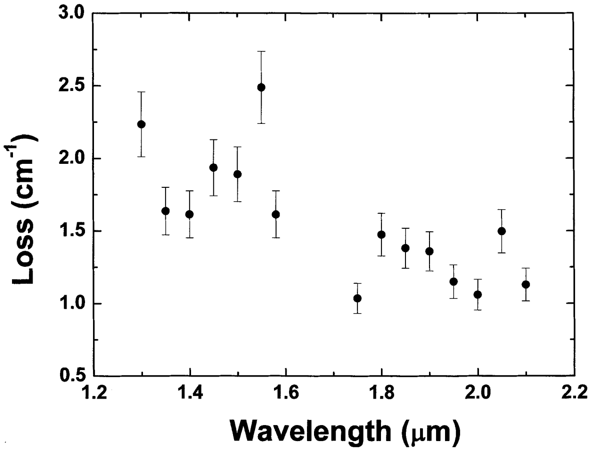


Fig. 4. Loss coefficients for the best waveguide plotted as a function of wavelength.

path. The wavelength tunability of the femtosecond OPO enabled the measurements over a wide spectral range from 1.3 to 2.1 μm. The streak was found to be stronger at shorter wavelengths, which could be due to the higher input power levels available and higher losses of the transmission optics at longer wavelengths. As shown in the magnified parts of Figs. 2(a) and 3(a), the section of the path comprising only the scattered light from the waveguide and devoid of any other spurious light is selected for further analysis.Figs. 2(b) and 3(b) show the data for selected portions of the scattered light at 1.5 and 2.0 μm, respectively. Measurements were performed for several waveguides and the best waveguide was chosen for wavelength dependent studies. Fig. 4 shows the loss coefficients extracted from the linear fit to the data were ~ 1.15–2.55 cm^{-1}, corresponding to propagation losses of 5–11 dB/cm. The selection of the particular set of data points from the plots of Figs. 2(b) and 3(b) has a significant bearing on the slope of the graph and, thereby, the loss coefficient. This is taken into account by the error bars depicted in Fig. 4. Since the loss coefficient is derived directly from the fit, special care was taken in avoiding the spurious spikes arising from dust particles and defects. We clearly observe higher losses in the 1.5-μm range compared to the 2.0-μm range. We expect the major contributions to the loss to be from absorption and scattering from the combination of waveguide and Al$_2$O$_3$ (Alox) layers. Also, due to large peak powers of the femtosecond pulses, the presence of two-photon absorption (TPA) at wavelengths below 1.7 μm would result in increased loss. That the TPA is an intensity-dependent process, while absorption and scattering are not, would enable us to separate the TPA contribution from others using simple nonlinear transmission data.

We performed the loss measurements for different input powers of ~2, ~5, and ~15 mW. Fig. 5 depicts the scattering profiles and the corresponding data along with the fits, which was obtained for a single and best waveguide at 1.55 μm. As the intensity increased, the scattering at the input facet also increased, thereby reducing the selected portion of waveguide for further analysis. With increasing input intensity the slope of the fit increased and thereby the overall loss. Typical loss values at 1.55 μm increased from ~ 1.18 cm^{-1} for an input power ~2 mW to 2.05 cm^{-1} for ~15 mW. We also performed wavelength-dependent studies of loss using the wavelength tunability of the femtosecond OPO. Fig. 6 shows the loss coefficients measured for wavelengths ranging from 1.41 to 1.57 μm. The lowest set of data (solid squares) were obtained for an input power of ~2 mW before the input microscope objective. As the power was increased, the loss increased systematically for all the wavelengths under study. The data represented by open circles were obtained for ~5 mW and the data shown in solid triangles were recorded with ~15 mW of input power. The loss coefficient was ~ 1.0 cm^{-1} for lower powers and increased to ~ 1.5 cm^{-1} and ~ 2.0 cm^{-1}, respectively, for higher powers. A simple and straightforward explanation for the observed data is that at lower input intensities, the scattering and absorption are the major contributors to loss and with increasing intensities TPA becomes prominent and hence the overall loss increases. Our results on other waveguides with different widths suggest that the loss coefficient varied from a minimum of ~ 0.9 cm^{-1} for input powers of ~2 mW to a maximum of ~ 3.0 cm^{-1} for an input power of ~15 mW. While the knowledge of loss dependence on the waveguide width is interesting in itself, our main goal in the present study was to investigate the applicability criteria of scattering technique as a means of identifying the different contributions to the overall loss in semiconductor nonlinear waveguides.

Fig. 7 depicts the variation in loss as a function of input power for specific wavelengths in the best waveguide. The loss in-

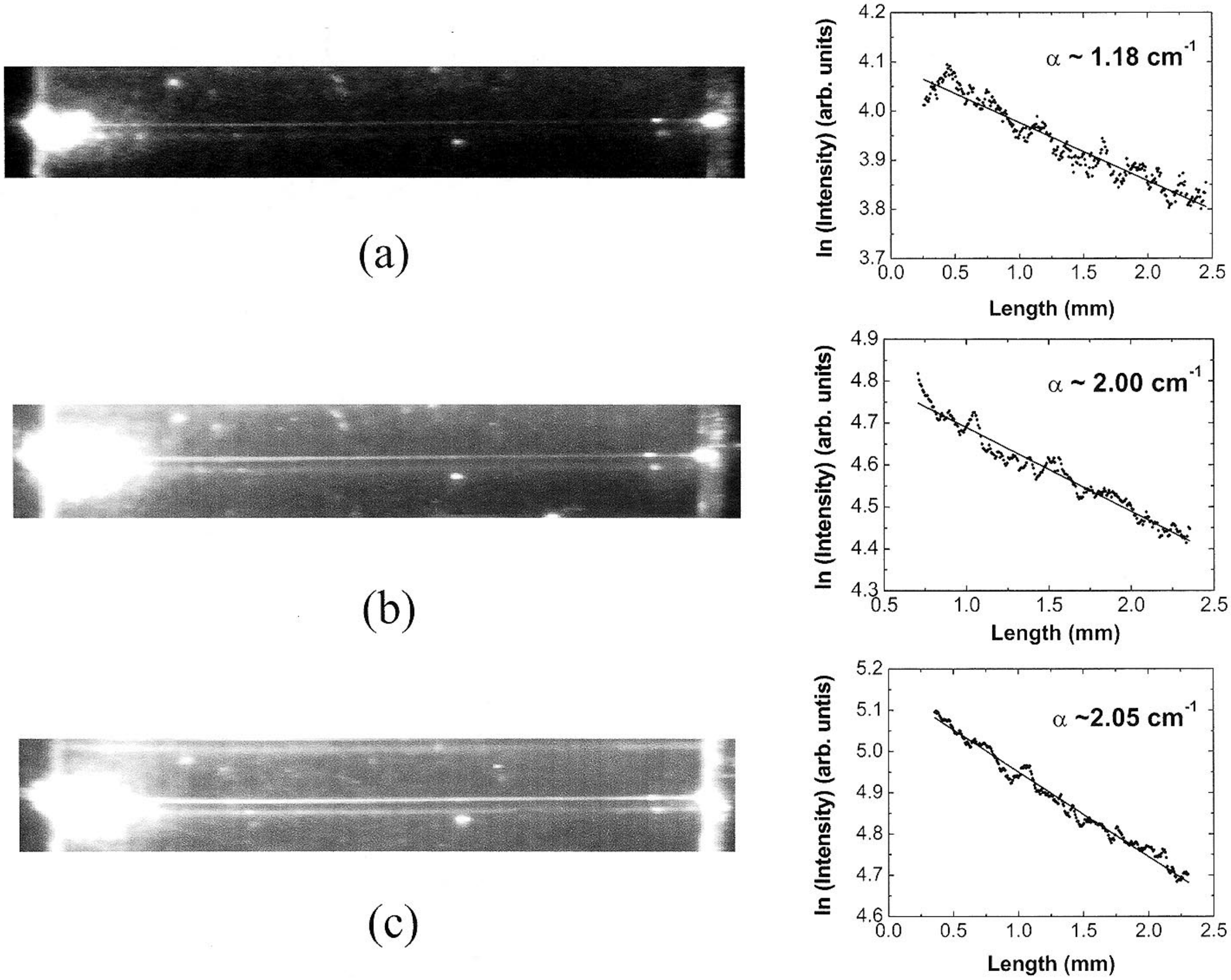


Fig. 5. Scattering profiles and the data with corresponding fits at 1.55 μm for: (a) ~2 mW; (b) ~5 mW; and (c) ~15 mW.

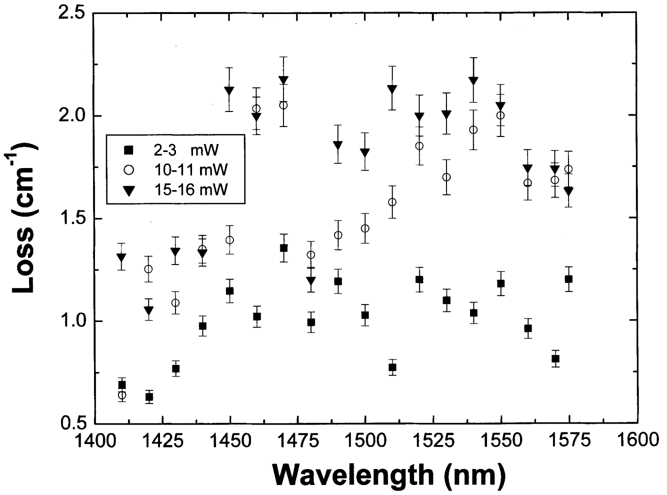


Fig. 6. Loss coefficients plotted as a function of wavelength for different input intensities. Squares (■): ~ 2mW. Open circles (○): ~ 5mW. Inverted triangles (▼): ~ 15mW.

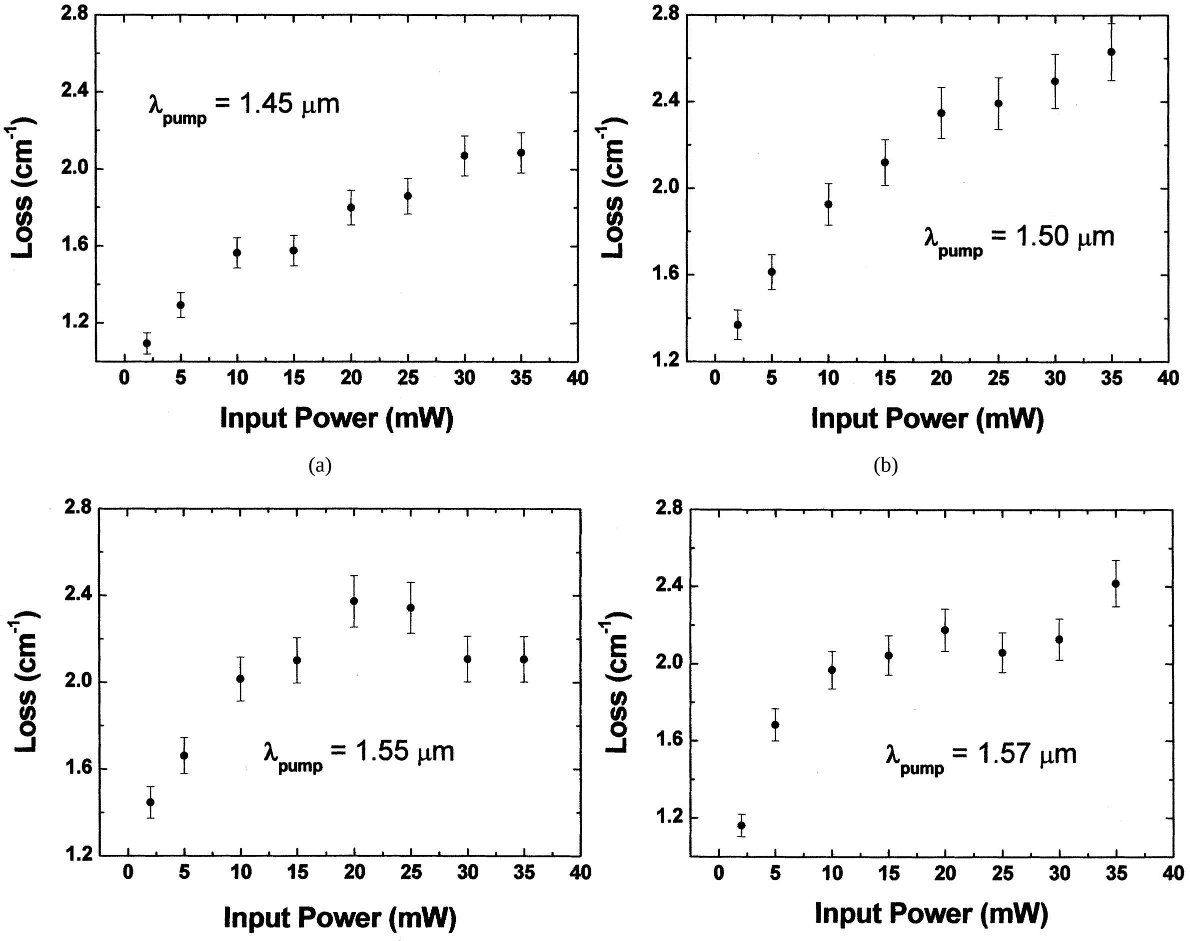
creased from ~ 1 cm^{-1} to ~ 2.5 cm^{-1} with an increase in input power from ~ 5 mW to ~ 25 mW. It can be seen from the plots that loss coefficient remains relatively constant beyond the input power level of ~ 25 mW. These observations support the argument that at higher input powers we have an extra contribution to the total loss arising from TPA. In order to investigate the magnitude of TPA, we undertook intensity dependent transmission measurements for the best waveguide with TE input polarization. Representative results of these studies at 1.48 and 1.55 μm are shown in Fig. 8(a) and (b). The nonlinear behavior of the data (solid circles) confirms the presence of TPA. Using a simple model and the data, we evaluated the TPA coefficient at these wavelengths. The transmitted of optical intensity in a semiconductor nonlinear medium is best described by the equation [36], [37]

$$\frac{\mathbf{dI(r,z,t)}}{\mathbf{dz}} = -\boldsymbol{\alpha}_0 \cdot I(r,z,t) - a \cdot \boldsymbol{\beta} \cdot I^2(r,z,t) \tag{1}$$

and the solution is of the form

$$\mathbf{I(r,z,t)} = \frac{\left(1-\mathbf{R}^2\right)\mathbf{I}(\mathbf{r},0,\mathbf{t})\mathrm{e}^{-\alpha_0 \cdot \mathbf{l}}}{1+\mathbf{a}\cdot\boldsymbol{\beta}\cdot(1-\mathbf{R})\cdot\mathbf{I}(\mathbf{r},0,\mathbf{t})\cdot\frac{\left(1-\mathrm{e}^{-\alpha_0 \cdot \mathbf{l}}\right)}{\boldsymbol{\alpha}_0}} \tag{2}$$

where α_0 is the linear absorption coefficient, β is the TPA coefficient, $\mathbf{l}$ is the length of the nonlinear medium, $\mathbf{R}$ is the reflectivity of the medium, $\mathbf{I(r,0,t)}$ is the incident irradiance, $\mathbf{I(r,z,t)}$ is the transmitted irradiance after a path length $\mathbf{z}$, and



(a) (b)

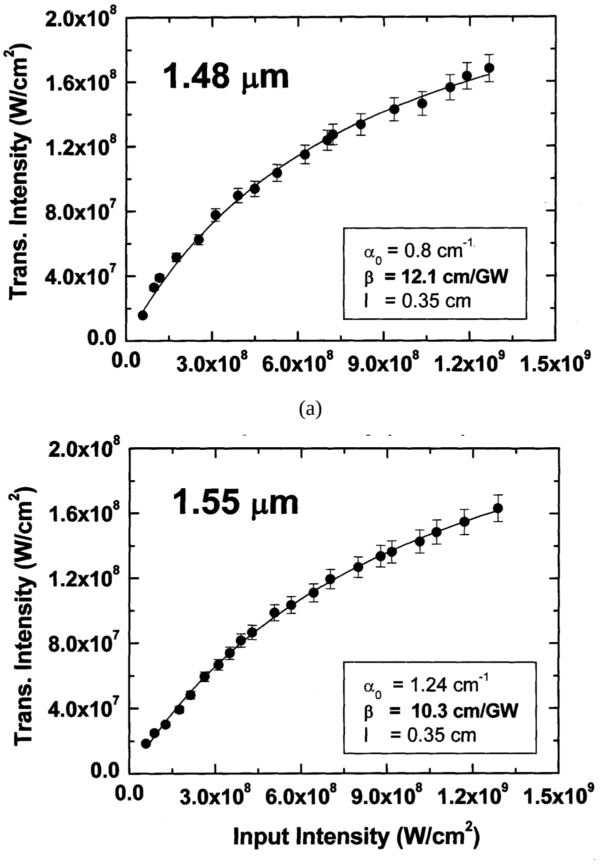
(c) (d)

Fig. 7. Loss coefficients for the best waveguide plotted as a function of input intensity at different wavelengths: (a) 1.45, (b) 1.50, (c) 1.55, and (d) 1.57 μm.

a is the modal structure factor arising from the average of the nonlinear interaction process over the transverse modal profile [36]–[40]. For obtaining the theoretical fits to the data, we used values of a $\sim$ 0.5, $R \sim 0.3$, and $l = 0.35$ for the sample. The input irradiance at the waveguide entrance was calculated taking into account the transmission of the objectives (90%) and reflection from the input facet (30%).

Fig. 8(a) and (b) shows nonlinear transmission data (solid circles) obtained for our waveguides at 1.48 and 1.55 μm and the corresponding fits (solid lines) obtained using (2). The three major factors influencing the peak intensities within waveguide are estimations of the coupling efficiency, the mode area, and the beam waist at focus of the microscope objective. All these parameters have been considered while calculating the peak intensities at the start of the waveguide, and the typical values obtained were $\sim$ 0.1–1.5 GW/cm^2. To obtain the values of β, we fixed α_0 at the value corresponding to our measurements at low input powers ($\sim$ 2 mW) and fitted the theoretical model to our experimental data. The loss coefficient α_0 is independent of input intensity and contains linear absorption due to Alox layers and scattering from imperfections at the boundaries of Alox and waveguide [41]–[44]. From intensity-dependent studies of the overall loss, depicted in Fig. 5, we obtained a loss coefficient of $\sim$ 0.8–1.2 cm^{-1} for an input power of $\sim$ 2 mW in the 1.45–1.58-μm range. Given the low input intensities in these measurements, we expect this loss to be due only to linear absorption and scattering and, hence, values of $\alpha_0 \sim$ 0.8–1.2 cm^{-1} were used to fit the data. In a separate experiment, the value of loss coefficient obtained using a CW FP method was $\sim$ 1 cm^{-1} at 1.32 μm, consistent with the values measured using the scattering technique at powers of $\sim$ 2 mW. These measurements, therefore, support our assumption of the absence of any TPA in our scattering measurements for input powers $\leq$ 2 mW. Fig. 9 shows the values of β ($\sim$ 10–20 cm/GW) obtained in the wavelength range from 1.43 to 1.70 μm. The error bars depicted in the figure are indicative of the inaccuracies in the calculation of input irradiance and the estimation of coupling efficiency.

There are several earlier reports on the TPA measurements in bulk GaAs, waveguides of GaAs, AlGaAs, and GaAs–AlGaAs [36]–[40], [45]–[52]. From their measurements on anisotropic two-photon transitions in GaAs–AlGaAs multiple-quantum-well waveguides, Yang *et al.* [37], [38] report values of TPA coefficient β ranging from 0 to 12 cm/GW in the wavelength range of 1.49–1.66 μm. Their optical source was a mode-locked YLF laser delivering 4–6-ps pulses. Villeneuve [39] obtained β values of $\sim$ 0.1–1.2 cm/GW for AlGaAs multiple-quantum-well waveguides near half the band gap. Villeneuve [40] also obtained β values of $\sim$ 5–30 cm/GW



(a)

(b)

Fig. 8. Nonlinear transmission data for the best waveguide plotted as a function of input intensity within the waveguide. The scattered points are the experimental data and the solid line is the fit given by (2) at (a) 1.55 and (b) 1.48 μm.

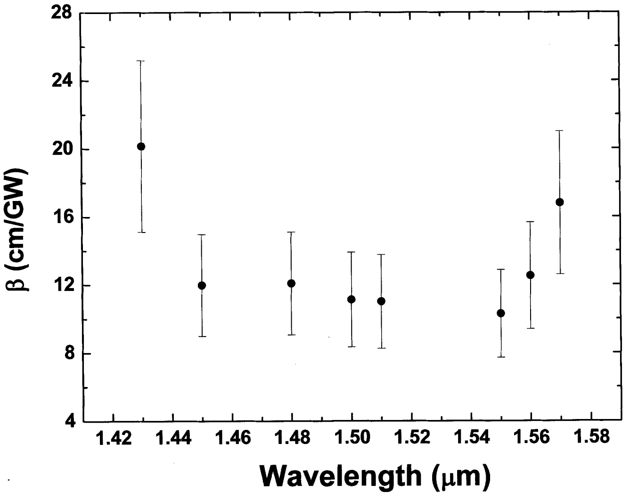


Fig. 9. TPA coefficient (β) plotted as a function of wavelength.

over a wavelength range of 1.70–1.45 μm for GaAs waveguides using 6–10-ps pulses from a color center laser. Tsang [45] investigated the polarization and field dependent TPA in GaAs–AlGaAs multiquantum-well waveguides in the half-band gap spectral region. The value of β obtained from their studies was $\sim$ 1.1 cm/GW at 1.55 μm using TE polarization for the input pulses. The value of β dropped by about seven times for the TM polarization. Islam *et al.* [48] presented their nonlinear spectroscopy measurements near half-gap in the bulk and quantum-well GaAs–AlGaAs waveguides. They obtained a TPA coefficient of $\sim$ 0.026 cm/GW for the bulk material and an average value of $\sim$ 0.65 cm/GW for the quantum-well waveguide in the 1.66–1.70-μm region. They also observed large nonlinear phase shifts while using 360-fs pulses from a color center laser. The estimated peak intensities within their waveguides were $\sim$ 10 GW/cm^2. The magnitude of TPA coefficients obtained in the present study ($\sim$ 0.9–2.0 $\times$ 10^{-8} cm/W) matches very well with the theoretical values (0.1–1.5 $\times$ 10^{-8} cm/W) of bulk GaAs reported by Khurgin *et al.* [52] and those obtained experimentally by Villeneuve *et al.* [40] (0.5–3.3 $\times$ 10^{-8} cm/W) for GaAs waveguides. The increase in the TPA values at higher wavelengths in the present study could be due to the large uncertainties in the calculation of the peak intensities within the waveguide for the reasons discussed in previous section. Moreover, the OPO used for the experiments has tuning range up to 1.58 μm only (due to mirror coatings) and near this wavelength range there is a possibility of the beam shape not being ideal, thereby leading to even larger errors in the calculations of waveguide intensities. Interestingly, the experimental TPA values of Villeneuve *et al.* [40] do show a small increase near 1.6 μm, as observed in our studies.

Since TPA is an intensity-dependent process, it will be strongly influenced by the peak pulse intensity within the waveguide. This, in turn, can vary drastically due to possible pulse-broadening effects arising from linear and nonlinear propagation effects. The most common mechanisms responsible for temporal pulse broadening within the waveguide are the linear group velocity dispersion (GVD) and nonlinear refraction (n_2) induced self-phase modulation (SPM). We performed a simple theoretical estimate of pulse broadening due to GVD. Since it is difficult to calculate the effective refractive indices and dispersion relations for the actual structure, we used the data for GaAs under the assumption that the actual dispersion relations are not significantly different. Using the standard Afromowitz [53] model, we evaluated the dispersion length and from it the pulse broadening in our 3.5-mm sample. The pulse broadening due to GVD can be expressed in terms of simple equation

$$\frac{\Delta\tau_{\mathbf{z}}}{\Delta\tau_0} = \sqrt{\left(1 + \frac{Z^2}{Z_D^2}\right)} \tag{3}$$

where $\Delta\tau_0$ is the input pulse duration, $\Delta\tau_Z$ is the pulse duration after propagating through a distance Z, and Z_D is the dispersion length given by

$$\mathbf{Z_D} = \frac{\Delta\tau_0^2}{4\ln(2)} \cdot \left[\frac{\mathbf{d^2k}}{\mathbf{d}\boldsymbol{\omega}^2}\right]^{-1} \tag{4}$$

where $d^2k/d\omega^2$ is the second-order dispersion. In our experiment, the input pulse duration was $\Delta\tau_0 \sim 250$ fs. Using (4), we estimated the pulse broadening to be $\sim$ 1.02 times the initial pulsewidth, which is negligibly small to be considered as having any effect on the pulse peak intensity and hence the TPA coefficient calculations. However, due to large peak powers of

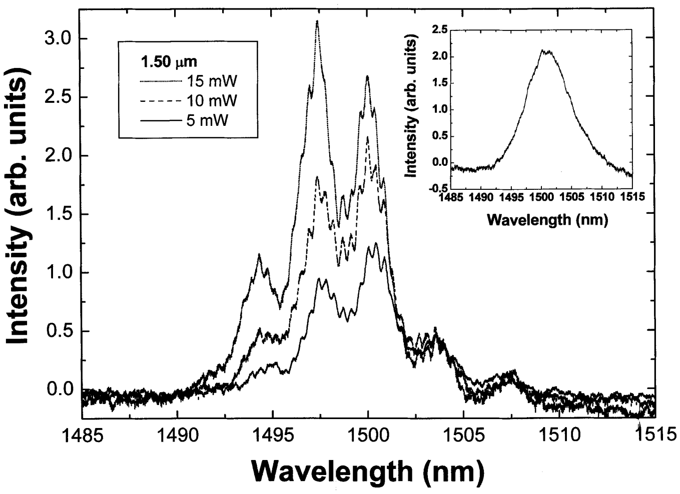


Fig. 10. Transmitted spectra obtained for the best waveguide at 1.5 μm. Inset: the input spectrum.

the femtosecond pulses used, we also considered the possibility of pulse broadening due to SPM within the waveguide. Fig. 10 shows the typical transmitted spectrum for the best waveguide obtained for various average input powers at 1.5 μm, with the input spectrum shown in the inset. The strong modulations in the spectra are indicative of SPM within the waveguide. The observed five-peak spectrum, obtained with an input power of $\sim$ 15 mW, indicates the maximum nonlinear phase shift induced at the peak of the pulse is $\sim 4.5\pi$ [54]. A simple estimate using the peak intensities at this power level leads to a value of $n_2 \sim 9 \times 10^{-13}$ cm^2/W, about two times larger than the values obtained in GaAs–AlGaAs waveguides studied by Yang *et al.* [38]. Similar measurements at 1.45 and 1.55 mm yielded n_2 values of $\sim 7 \times 10^{-13}$ cm^2/W and $\sim 3 \times 10^{-13}$ cm^2/W, respectively. However, as discussed above, due to the uncertainties in the exact magnitude of pulse broadening within the waveguide, a $\sim$50% error in the estimate of peak intensities within the waveguide would influence the β and n_2 values by $\sim$50% also. Villeneuve, *et al.* [39], [40] evaluated the TPA coefficients and n_2 for both AlGaAs and GaAs–AlGaAs waveguides. They obtain an n_2 value of $\sim 4 \times 10^{-13}$ cm^2/W for GaAs/AlGaAs quantum-well waveguides at 1.5 μm.

Similar measurements could be performed at wavelengths longer than 1.6 μm. Our initial data indicates that the loss is intensity dependent at these wavelengths also, which could be due to the contribution of multiphoton absorption (three-photon, in this case) to the overall loss. Further detailed studies, which are in progress, will enable better understanding of the results. Measurements of loss were also performed for different waveguide modes (TE$_{00}$ and other higher order modes). However, the results did not reveal any drastic variation in the loss coefficients, confirming good confinement within the waveguide. Loss measurements were also performed in the best waveguide for different polarization configurations of the input beam, namely TE, TM, and TE+TM. The losses were found to be lowest for TE polarization compared to the other two configurations. The main advantage of using an OPO is the continuous tunability achievable over the entire wavelength range in the near- and mid-IR. An ideal way of complete characterization of semiconductor waveguide losses in the near- and mid-IR would involve the study of loss by the scattering technique using a femtosecond OPO initially, followed by the FP technique using a CW-OPO, thus enabling us to picture the interaction of short pulses within the medium and the actual propagation losses.

IV. CONCLUSIONS

In summary, we have presented measurements of optical loss in GaAs–Al$_2$O$_3$ nonlinear waveguides in the near infrared, including the important telecommunication window (near 1.55 μm), and near 2.0 μm, where these waveguides have already been shown to be strong candidates for nonlinear frequency conversion. Using the scattering technique and femtosecond pulses from an OPO, the losses were evaluated over an extended wavelength range from 1.3 to 2.1 μm. A systematic study involving intensity and wavelength dependence revealed the magnitude of TPA and enabled us to separate out its contribution to the overall loss. The TPA coefficient was estimated to be $\sim$9–20 cm/GW in the 1.45–1.55-μm wavelength range, representing a contribution of $\sim$ 1–1.5 cm^{-1} to the overall loss observed. Due to availability of large peak powers in the femtosecond pulses we also observed strong nonlinear phase shift in the waveguides, useful for applications in ultrafast optical switching. Further studies involving oxidized and nonoxidized samples would enable us to isolate the contribution of absorption and scattering from Alox alone. We believe that this technique combined with the wavelength flexibility of the femtosecond OPO represents a general and simple method for accurate determination of waveguide losses across the near- and mid-IR wavelengths where few other practical optical sources are readily available.

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Soma Venugopal Rao was born in Hyderabad, India, in 1972. He received the B.Sc. degree from Osmania University, and the M.Sc and Ph.D. degrees in physics from the University of Hyderabad, Hyderabad, India, in 1992, 1994, and 2000, respectively. His thesis involved the studies of third-order nonlinear optical properties and excited-state dynamics in C_{60}, Porphyrins, and Phthalocyanines using incoherent light.

Since August 2000, he has been a Research Assistant with the University of St. Andrews, Fife, Scotland, U.K. He has been involved in the development of novel mid-infrared sources and investigating the applicability of semiconductors for frequency conversion in the near and mid-infrared. His research interests include third-order nonlinear optical properties, excited-state dynamics, nonlinear frequency conversion, optical parametric oscillators, and loss measurements in waveguides. He is the author of 14 journal publications and 12 conference publications.

Dr. Rao is a Life Member of the Indian Laser Association.

Konstantinos Moutzouris was born in Athens, Greece, in 1974. He received the degree (Ptychion) in physics from the National and Kapodistrian University of Athens, Athens, Greece, in 1998. He is currently working toward the Ph.D. degree with the Semiconductor Nonlinear Optics Group at St. Andrews University, Fife, Scotland, U.K., funded by the EPSRC.

He is an author/coauthor of more than ten papers in international journals and conference proceedings. His research activities include the exploitation of novel techniques for nonlinear frequency conversion in isotropic semiconductors and the use of new nonlinear materials for near- and mid-IR light sources.

Majid Ebrahimzadeh is the recipient of a Royal Society Research Fellowship and is a Reader in the School of Physics and Astronomy, University of St. Andrews, Fife, Scotland, U.K. He has been conducting research in applied nonlinear optics and frequency conversion for over a decade and has contributed to the advancement of optical parametric oscillators for the continuous-wave, nanosecond-pulsed, and ultrafast picosecond and femtosecond time domain. His work on parametric frequency conversion has led to over 80 journal publications and eight book chapters and reviews.

Dr. Ebrahimzadeh has served as the Technical Program Committee Chair and Short Course Instructor at the Conference on Lasers and Electro-Optics and on the organizing committee of several international conferences. He has been a Guest Editor of the *Journal of the Optical Society of America B* on optical parametric devices and Advisory Editor of *Optics Letters*.

Alfredo De Rossi was born in Rome, Italy, in 1971. He received the M.S. degree in electrical engineering from the Università La Sapienza, Rome, in 1997, and the Ph.D. degree in nonlinear optics from the "Università Roma III", Rome, in 2002.

In 1999, he joined the Corporate Research Laboratory of Thales Research and Technology (formerly Laboratoire Central de Recherches, Thomson-CSF), Orsay, France, in the framework of the European Commission funded project "OFCORSE". Since 2000, has been a permanent member of the Infrared Detection Group. His work involves electromagnetic modeling of infrared detectors, the design of prototype monolithic laser-diode sources for quantum cryptography, and a research program on nonlinear optics in integrated semiconductor structures. He is author or coauthor of 16 papers in international journals and holds two patents.

G. Gintz, photograph and biography not available at the time of publication.

Michel Calligaro was born in Bordeaux, France, in 1948. He graduated from the Institut National des Sciences Appliquées, Toulouse, France, in 1971, and received the 3° Cycle Doctor's degree in 1975.

He joined THOMSON-CSF, Orsay, France, in 1973. He has been working in the fields of microwaves diodes and semiconductors lasers and has been involved in the design and technology of silicon p-i-n diodes, GaAs IMPATT diodes, Si IMPATT diodes, and InP GUNN diodes for applications between 10–94 GHz. Since 1995, he has been involved in the technology of various semiconductors lasers and light-emitting diodes. He has been involved in several CEE projects: RAINBOW, GHIZO, OFCORSE 2, ULTRABRIGHT.

Valentin Ortiz was born in Lima, Peru, in 1972. He received the engineering degree from Ecole Nationale Supérieure de Physique de Grenoble, Grenoble, France, in 1996 and the Ph.D. degree in semiconductor physics from the University of Grenoble, Grenoble, France, in 1999. His Ph.D. thesis involved work on the growth and design of piezoelectric II-VI semiconductor-based devices (optical modulators, tunable lasers, etc.).

In 1999, he joined Thales Research and Technology, Orsay, France, where he works on the MBE growth of optoelectronic GaAs-based devices such as quantum-cascade lasers, nonlinear waveguides, and saturable absorbers. He is the author and co-author of 20 journal and conference papers and holds two patents on novel tunable laser devices.

Dr Ortiz received the "Prix du Jury" Young Scientist Award of Grenoble in 1999.

Vincent Berger was born in Saint-Amand, France, in 1967. He graduated from the Ecole Normale Supérieure, Paris, France, in 1988, and received the Ph.D. degree in solid-state physics from the University Paris VI, Paris, France, in 1992.

From 1990 to 1992, he was with the Laboratoire Central de Recherches, Thales Research and Technology (formerly Thomson-CSF), Orsay, France, working on intersubband transitions in quantum wells. He joined the Laboratoire d'Optique Appliquée, ENSTA-Ecole Polytechnique, for one year, working on femtosecond spectroscopy of semiconductors. From 1993 to 2001, he was with the Physics Laboratory of the Laboratoire Central de Recherches, Thales, working on mid-infrared detection in semiconductor heterostructures and nonlinear optics in heterostructures (frequency conversion), including photonic band gap materials. In 2001, be became a Professor at the University Denis Diderot–Paris 7, and is now Head of the Quantum Phenomena and Materials Laboratory. He has published around 100 papers in international journals, and has 15 patents.

Dr. Berger received the Fabry-De Gramont Award and the MIT Young Innovator Award in 2002 for his work on different schemes of phase-matching nonlinear optical processes in semiconductor waveguides.