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Measurements of optical loss in $GaAs/Al_2O_3$ nonlinear waveguides in the infrared using femtosecond scattering technique

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Abstract

We report measurements of optical loss in $GaAs/Al_2O_3$ nonlinear waveguides over the spectral range 1.3–2.1 μm in the infrared using a scattering technique. The optical source was a tunable femtosecond optical parametric oscillator (OPO) generating output pulses with durations of 200–250 fs at a repetition rate of ~90 MHz and an average power of ~50 mW. Loss coefficients of ~1.15–2.55 cm^{-1}, corresponding to losses of ~5–11 dB/cm were obtained from the measured data. The loss decreases with increasing wavelength due to the Rayleigh scattering contribution.

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Advances in the material research of III–V semiconductor nonlinear waveguides support the development of new photonic devices for a variety of applications such as wavelength mixing for telecommunications or infrared (IR) frequency conversion for spectroscopy and gas sensing. Accurate knowledge of the optical loss is important in the evaluation and implementation of resonant devices such as optical parametric oscillators (OPOs) where, due to the small available nonlinear gains, the loss can have a dramatic impact on the oscillation threshold. In single-pass devices, such as nonlinear frequency shifters, wavelength mixers, and harmonic generators [1,2], optical loss sets an upper limit to the maximum output power and conversion efficiency that may be achieved in the nonlinear process.

Losses in semiconductor waveguides are sometimes difficult to characterize due to the inaccurate knowledge of effective refractive indices and facet

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reflectivities. Over the past few years several techniques including the cutback method [3], prism coupling [4], photo-thermal deflection [5], and the Fabry–Perot (FP) interference method [6], have been employed for the evaluation of loss. Other techniques including internal modulation [7], photo-luminescence [8], optimized end-fire coupling [9], self-pumped phase conjugation [10], and the scattering technique [11] have all been tried and tested. While most of these techniques have been found to be suited for assessment of waveguides with losses greater than 1 dB/cm, they 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. However, even though the technique is simple, robust, and non-destructive 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 [12]. Scattering technique, on the other hand, is relatively uncomplicated without stringent demands on the optical source and has been successfully demonstrated in a variety of optical waveguides [13–16]. This technique is useful especially for measuring losses in the 1–10 dB/cm range. Moreover, for some waveguide applications in telecommunications involving division multiplexing (either DWDM or TDM) it is helpful to use femtosecond (fs) pulses utilizing their large bandwidth. In such cases, the 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 information. The majority of loss measurements using this method (as well as other techniques) have to date been performed at discrete wavelengths in the IR using a variety of optical sources. Here we present 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 IR using the scattering technique by employing a tunable femtosecond OPO. The results of these measurements are important in the context of nonlinear frequency conversion experiments in the IR including second harmonic generation (SHG) [2], difference frequency generation [17,18], and parametric fluorescence [19] that have recently been demonstrated in such waveguides.

The schematic of experimental set up is shown in Fig. 1. The optical source was a Ti:sapphire-pumped femtosecond OPO based on periodically poled $LiNbO_3$ and configured in a semi-monolithic cavity design [20]. The OPO provided signal and idler pulses with duration of ~250 and ~200 fs, respectively, at ~90 MHz repetition rate. The signal pulses were tunable over a range of ~1.30–1.58 μm and the idler pulses in the range ~1.8–2.1 μm. Average signal and idler powers of 100 and 50 mW could be routinely obtained from the OPO over the respective wavelength ranges. An end-fire coupling rig was used for mounting the semiconductor waveguide samples. The TE-polarized input pulses from the OPO were focused into the waveguide using a 40× microscope objective and the transmitted pulses were collected using a second 20× microscope objective. An infrared camera was used for optimizing the coupled light into the waveguide. The technique [10,11] is based on measuring mode propagation losses of the channel waveguide by directly monitoring the scattered light intensity out of the plane of the guide using an imaging system comprising a microscope, an IR camera, a frame grabber card, and a computer to analyze the data, as depicted in Fig. 1.

We expect the intensity of the light scattered normal to the waveguide at a given point 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 form 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

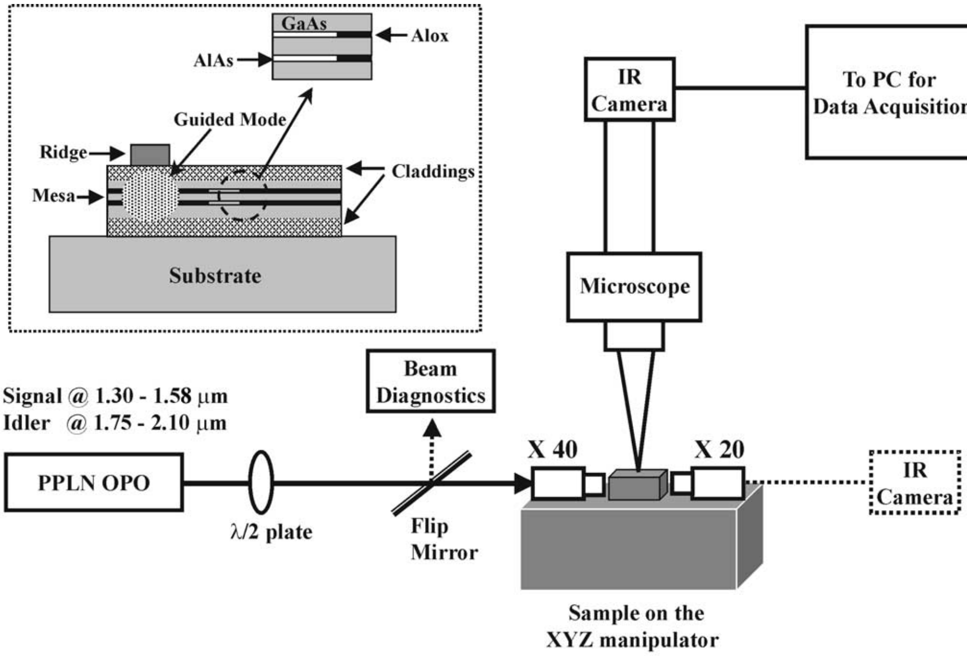

Fig. 1. Schematic of the experimental set up used for loss measurements. Inset shows the structure of the sample used.

the start of the path, and α is the 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 re-written in the form $\ln(I_L) = \ln(I_0) - \alpha L$. Therefore, by recording the scattered intensity along the guide and using a suitable algorithm based on the above equation, we can readily determine the loss coefficient, α. To increase the resolution, a mask was inserted above the sample to block the strong scattering at the input and output facets, as well as any residual reflected light from the top surface of the sample in the lateral directions.

The sample structure, shown in the inset of Fig. 1, was similar to the one used for the SHG experiment [1] and consisted of (GaAs $\langle 001 \rangle$ substrate)/1000 nm AlAs/1000 nm $Al_{0.7}Ga_{0.3}As$/4 $\times$ (37 nm AlAs/273 nm GaAs)/37 nm AlAs/1000 nm $Al_{0.7}Ga_{0.3}As$/30 nm GaAs. Results of other characterization studies on similar structures are presented in detail in our previous publications [21–23]. In the present study, we used a 3.5-mm sample that had several waveguides of different widths ranging from 2 to 6 μm. Figs. 2(a) and 3(a) show typical scattering profiles in the waveguide at 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 non-continuous 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 path. The wavelength versatility of the femtosecond OPO enabled the measurements over a wide wavelength 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 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

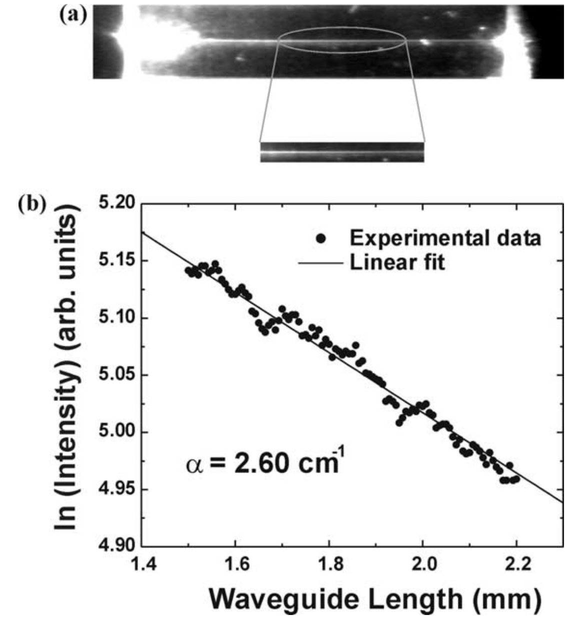

Fig. 2. (a) Photograph of a typical image of scattered light in the waveguide at 1.5 μm. Light is coupled into the waveguide at the left hand side. Magnified image of the area is selected for loss evaluation. (b) Intensity profile of the scattered light for a 2.6 cm^{-1} loss waveguide at 1.5 μm.

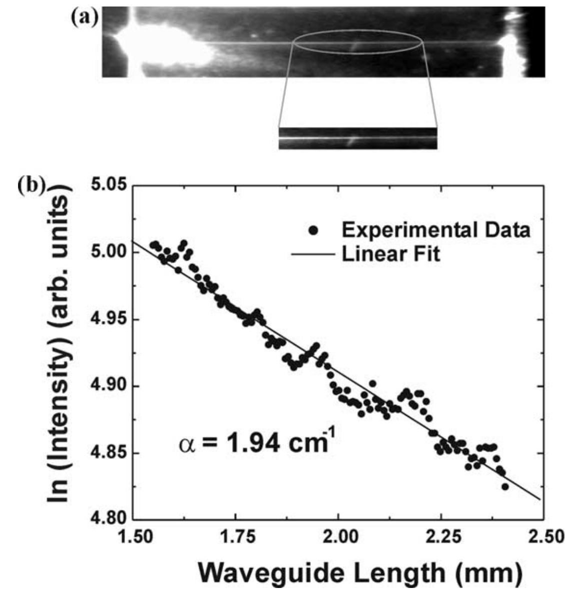

Fig. 3. (a) Photograph of a typical image of scattered light in the waveguide at 2.0 μm. (b) Intensity profile of the scattered light for a 1.94 cm^{-1} loss waveguide at 2.0 μm.

other spurious light is selected for further analysis. Figs. 2(b) and 3(b) show the data for such selected portions of the scattered light at 1.5 μm and 2.0 μm, respectively. Measurements were performed for various waveguides and the best waveguide was chosen for wavelength dependent studies. 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 main source of error in the calculation arises from the selection of proper region of scattered light and the fitting procedures. Further improvements to the accuracy are possible with longer waveguide samples.

Fig. 4 depicts the loss variation for different wavelengths. We can clearly observe higher losses in the 1.5 μm range compared to the 2.0 μm range. This is expected since the major contribution to the loss would be from Rayleigh scattering experienced due to the Al_2O_3 and the waveguide imperfections, which scales as inverse of second power of wavelength. Also, due to large peak powers of the femtosecond pulses, the presence of any two-photon absorption (TPA) at wavelengths below 1.7 μm [24–28] would result in an increased loss. Typical peak input intensities within the waveguide were estimated to be ~0.1–3.0 GW/cm^2. Our initial intensity dependent loss measurements confirm that TPA plays an important role and could contribute significantly (as high as

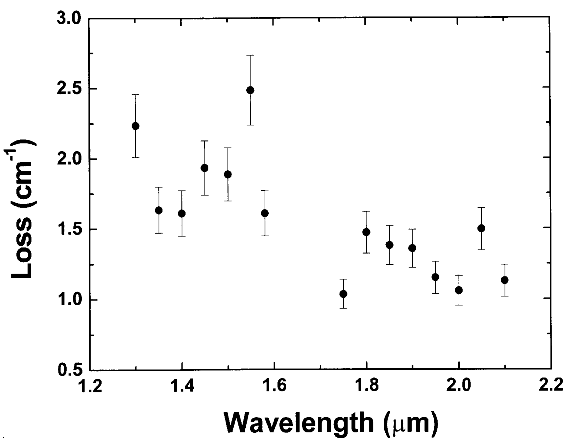

Fig. 4. Loss values for the best waveguide plotted as a function of wavelength.

$\sim$1.0 cm^{-1}) to the overall loss. However, a systematic study involving the waveguide transmission measurements as a function of input power at different wavelengths is in progress to identify the exact threshold and magnitude of the TPA coefficient enabling us to separate this contribution from scattering and absorption losses. The results of these studies will be a subject of a future report. Measurements of loss were also performed for different waveguide modes (TE_{00} and other higher order modes) and the results did not reveal any drastic variation in the loss coefficients, confirming good confinement within the waveguide. Loss measurements were also carried out in the best waveguide for different polarization configurations of the input beam, namely TE, TM, and TE + TM. The losses were found to be minimum for TE polarization compared to the other two configurations. The loss coefficient measured for the same waveguides at 1.3 μm using the cw FP interference technique was $\sim$1.5 cm^{-1}, which is in good agreement with the values obtained using the present technique. Work is also in progress to measure the losses at similar wavelengths using the FP technique with a tunable cw OPO as the optical source.

In summary, we have presented measurements of optical loss in $GaAs/Al_2O_3$ nonlinear waveguides in the telecommunication window (near 1.55 μm) and in a new spectral range near 2.0 μm, where these waveguides are proven to be strong candidates for nonlinear frequency conversion. Using the scattering technique and femtosecond pulses from an OPO for the first time, the losses were evaluated over an extended wavelength range from 1.3 to 2.1 μm. We believe that this technique combined with the wavelength versatility of the femtosecond OPO represents a general and simple method for accurate determination of waveguide losses across the near- and mid-IR where few other practical optical sources are available.

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