This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication.

All-optical broadband variable optical attenuator based on an As_2Se_3 microwire

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***Abstract*—We propose and demonstrate an all-optical broadband variable attenuator based on an As_2Se_3 microwire. The attenuation of the proposed fiber device as a function of the irradiating power is evaluated for the spectral regions of 1550 nm and 1850 nm, showing that photoinduced attenuation can be realized over a wide spectral range. We further assess the dynamic response of this variable attenuator upon modulating the amplitude of the irradiating beam.**

***Index Terms*— Optical fiber devices, attenuation measurements, optical waveguides, photochromism.**

I. Introduction

CHALCOGENIDE (ChG) glasses are an important class of materials for photonics applications. The optical properties of these glasses have driven the development of photonic devices such as waveguides, which are of great interest for optical systems due to their wide transmission window and strong nonlinearities [1]. As an example, the transparency window of amorphous As_2Se_3 ranges from 0.8 to 10 µm [2], enabling mid-infrared light guiding and making it useful for optical instrumentation, medicine and defense applications.

An interesting aspect of ChG glasses is the variety of photoinduced phenomena observed by illumination with photons at a wavelength that is sufficiently energetic to reach the bandgap threshold. For instance, amorphous As_2Se_3 has a bandgap energy $E_g = 1.79$ eV ($\lambda_g = 0.7$ µm), and irradiation with light at wavelengths close to λ_g has shown to generate dichroism, structural changes and photodarkening [3-6]. Furthermore, photosensitivity in As_2Se_3 has allowed for the fabrication of Bragg gratings in chalcogenide microwires, leading to new devices for nonlinear optics and sensing applications in the near- to mid-IR spectral region [7, 8]

Photodarkening is typically associated to structural changes, which in turn affect the electronic states of the glass [9]. During illumination, transient and metastable effects account for the total photodarkening. While the transient changes decay upon switching off the illumination, metastable photodarkening is reversible on long time scales and by annealing [9]. Once the metastable state is reached, further illumination induces only transient changes [9, 10]. The photoinduced structural changes are described in terms of charging and movement of layer- or chain-like clusters of atoms [10]. Furthermore, illumination also leads to other effects associated to structural changes such as photoexpansion, photorefraction and changes in the optical band gap [9-11].

Transient photodarkening is one of the most extensively studied effects in ChG glassy films, and it represents a considerable fraction of the total changes observed in these glasses [9-12]. In this paper, we demonstrate broadband adjustable attenuation in an As_2Se_3 microwire via photodarkening. The attenuation performance of the proposed fiber device as a function of the irradiating power is evaluated for the spectral regions of 1550 nm and 1850 nm, showing that the device operates well over a broad spectral range. We further evaluate the dynamic response of this variable all-optical attenuator upon modulating the amplitude of the irradiating beam.

II. Transient Photodarkening In The As_2Se_3 Microwire

Broadband attenuation under photoexposition of the microwire arises mainly from photodarkening in the As_2Se_3 core. The total increase in the attenuation coefficient during illumination is the sum of the transient and the metastable photodarkening [9]. As shown in ChG glassy films, the attenuation can be modulated via transient photodarkening upon successive cycles of illumination [9, 10]. Transient and metastable changes occur for short illumination times, and the metastable part accumulates with each successive illumination.

The transient photodarkening effects observed during illumination of ChG glasses involve nonradiative recombination of photexcited charge carriers and defects [9-12]. Changes in absorption coefficient $\Delta\alpha(t)$ owing to

Manuscript received XXX X, 2012.
The authors are grateful to Coractive High-Tech for providing Tm-doped silica fiber used in the experiment. This work was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Fonds Québecois de Recherche sur la Nature et les Technologies (FQRNT). Financial support from DGAPA-UNAM, grant IN102112, is also acknowledged.
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transient photodarkening are typically described by a stretched exponential function [9-12]:

$$\Delta\alpha(t) = \Delta\alpha_{\max}\left[1 - \exp\left\{-\left(\frac{t}{\tau}\right)^{\beta}\right\}\right] \quad (1)$$

where $\Delta\alpha_{\max}$ is the maximum change in absorption, τ is the characteristic time and β the dispersion parameter. The stretched exponential function has been widely used to describe the kinetics of changes in amorphous semiconductors, and has been confirmed as a good representation for photodarkening and other photoinduced phenomena in chalcogenide thin films [10-14]. Experimental studies have shown that photodarkening is a wavelength dependent effect; in particular, $\Delta\alpha_{\max}$ has been reported to decrease with increasing wavelength [11, 12]. Photodarkening can thus provide a means for inducing constant attenuation in the As_2Se_3 microwire upon continuous illumination. Moreover, the attenuation can be modulated upon switching the illumination on and off.

III. Experimental Setup

The microwire used in our experiments is made from a single-mode As_2Se_3 fiber over which a PolyMethyl MethAcrylate (PMMA) tube is collapsed. The assembly is subsequently heated and stretched to form a 15 cm long tapered waveguide with a microwire section of uniform diameter [15]. The microwire section is 10 cm long and consists of an As_2Se_3 core (0.6 µm diameter) covered by a PMMA layer (15 µm diameter). Typical insertion losses of these microwires are 8 dB at a wavelength of 1550 nm, arising mostly from Fresnel reflections (~1.1 dB), mode mismatch loss (~2 dB) at both coupling interfaces between the chalcogenide fiber and standard single mode fibers (SMF-28e), and ~4.9 dB loss due to propagation in the wire section. These values do not change significantly for the 1850 nm wavelength region.

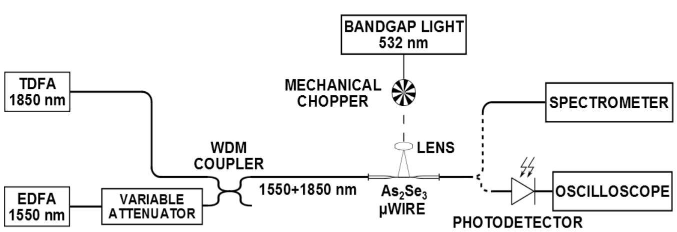

Fig. 1. Experimental setup for monitoring the photoinduced broadband attenuation in a chalcogenide microwire.

The transmission spectrum of the device was probed simultaneously over the wavelength bands of 1520-1565 nm and 1810-1890 nm using the setup shown in Fig. 1. For the first wavelength region, we used the amplified-spontaneous emission (ASE) from an Erbium-doped fiber amplifier (EDFA), whereas the ASE from a Thulium-doped fiber (TDFA) was used as the light source for the band centered at 1850 nm. These broadband sources were coupled into the microwire by means of a wavelength-division multiplexer (WDM).

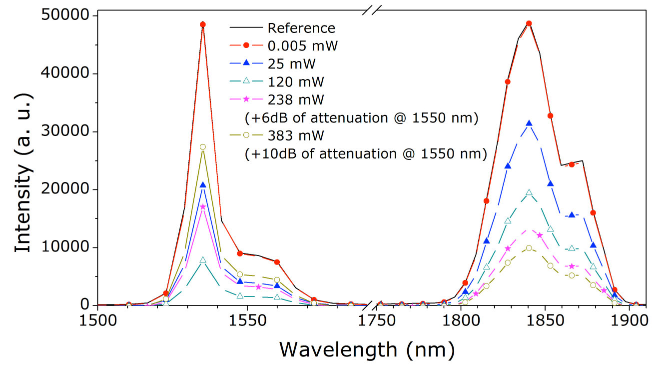

Fig. 2. Transmitted power of the EDFA and TDFA through the microwire as a function of the bandgap light power.

Transient photodarkening was induced in the microwire using bandgap light from a CW pump laser (Melles-Griot, 85 GHS 305) at a wavelength of 532 nm and a 1 mm beam spot size. In order to increase the irradiated section of the microwire, the beam was expanded with a spherical lens yielding a beam diameter of approximately 4 mm. The polarization of this pump beam was oriented along the axis of the fiber and the lensing effect from the PMMA layer of the microwire (n = 1.49) adequately conveyed all the rays impinging on the surface towards the As_2Se_3 core. Steady-state transmission measurements were obtained irradiating the microwire and monitoring the output signal with a solid-state spectrometer (Ocean Optics, NIRQuest) covering the spectral range of 900 nm to 2500 nm. For dynamic measurements, a mechanical chopper was used to modulate the bandgap light at a frequency of 500 Hz and with a 50% duty cycle. For these measurements the output from the microwire was connected to an InGaAs photodetector with 25 ns rise time and a 1200-2600 nm wavelength range (Thorlabs, DET10D). The signal from the photodetector was then monitored by an oscilloscope with a bandwidth of 600 MHz (Agilent 54621A).

IV. Results and Discussion

Fig. 2 shows the power spectrum of the EDFA and TDFA through the chalcogenide microwire with increasing amounts of bandgap light. As seen in the figure, the transmission spectrum of the microwire decreases in amplitude upon increasing the bandgap light power. Noticeably, the attenuation for both spectral bands increases simultaneously as a function of power; thus, broadband photoinduced attenuation is effectively achieved. The increase in attenuation is also wavelength dependent; notice that the last two curves in Fig. 2 for the 1550 nm band required adjustments on the variable attenuator in the experimental setup. These were needed in order to overcome the larger attenuation obtained for this wavelength band.

To illustrate the wavelength dependence of the photoinduced attenuation, the transmission for several wavelengths within the two bands is shown in Fig. 3. As the bandgap light power increases, the photoinduced attenuation at shorter wavelengths is systematically larger than that obtained for longer wavelengths. This is further confirmed in Fig. 4 that depicts the photoinduced changes in transmission for four different wavelengths within both spectral bands. This wavelength dependence has been previously reported for transient photodarkening in As_2Se_3 thin films [11, 12], and seems to be preserved for the microwire. Although other aspects such as the confinement factor of the waveguide and photorefraction will also play a role in this wavelength dependency, our results are consistent with previous reports on transient photodarkening effects.

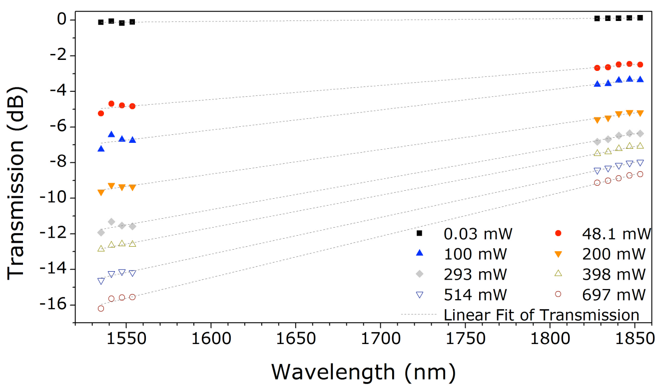

Fig. 3. Photoinduced attenuation as a function of bandgap light power.

It is interesting to notice in Fig. 4 that changes in attenuation are more pronounced for low powers of the bandgap light. This has also been observed in ChG glassy films owing to metastable photodarkening [9, 10]. These metastable changes occur for short illumination times and accumulate with each successive illumination. Our experimental results did not produce any evidence of metastable photodarkening being induced in the microwire; nonetheless, the photoinduced attenuation follows a similar trend.

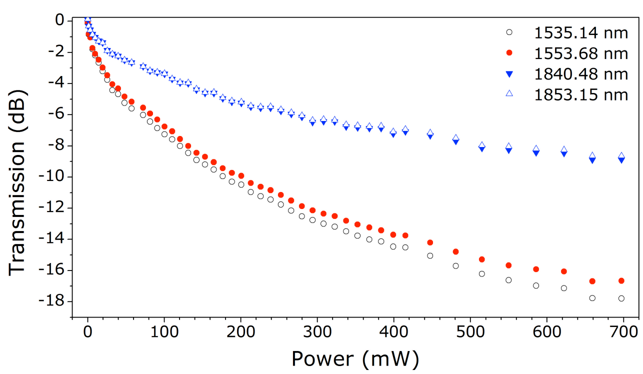

Fig. 4. Transmission at different wavelengths through the microwire as a function of bandgap light power.

The dynamics of the photoinduced attenuation are shown in Fig. 5, obtained upon modulation of the bandgap light and using the 1550 nm broadband source. While power transmission through the microwire steeply falls under sudden irradiation by the pump, withdrawal of the bandgap light enables a recovery of the transmission. The response time measured in these experiments was $\tau_c = 140$ µs for a 500 Hz modulation frequency. Fitting of the signal with the stretched exponential function (1) yields a dispersion parameter $\beta = 0.86$, which agrees well with those previously reported for transient photodarkening effects in ChG glassy films [9, 14]. Further measurements at different powers for the bandgap light showed that the characteristic time decreases with increasing power, which is also consistent with transient photodarkening effects [11, 12]. Only minor variations in the resulting fitting parameters (i.e., τ and β) were obtained from the experimental measurements of the 1850 nm broadband source. These results therefore suggest that photodarkening is the dominant effect driving the broadband photoinduced attenuation registered for the microwire. Nonetheless, contribution from other photoinduced effects will also play a role in the observed phenomenon.

Thermal effects, photorefraction and photoexpansion can indeed play a role in the attenuation of the microwire. The photoexpansion can significantly change the waveguide diameter at the point of illumination, which can lead to propagation loss simply due to mode mismatch and changes in the structure of the material. However, a key consideration is the time scale over which attenuation occurs leading us to point transient photodarkening as the main contributor to the observed dynamics. As an example, the time constants for transient photodarkening have shown to be shorter than those associated to photorefraction [11, 13]. The wavelength of the bandgap light will also affect the transient effects, owing mostly to the wavelength dependence of the penetration depth. In general, shorter wavelengths for the bandgap light are expected to yield smaller values for the dispersion parameter and longer time constants [13].

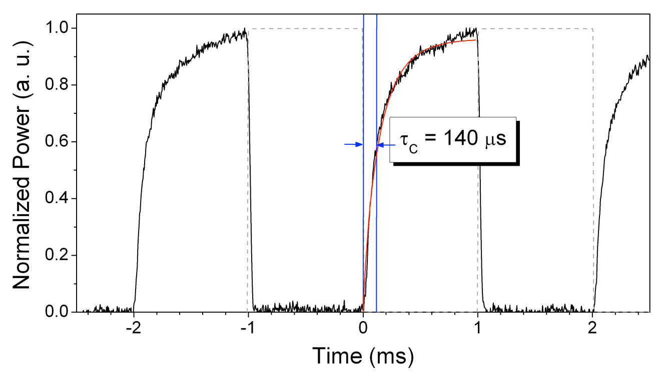

Fig. 5. Oscilloscope trace showing the photoinduced attenuation dynamics for a 500 Hz modulation frequency of the bandgap light (dashed line). The red line is the fitted stretched exponential function ($\tau = 139.7$ µs, $\beta = 0.86$).

As demonstrated with our experimental results, photoinduced effects in ChG glasses could be useful for realizing waveguide devices with optically adjustable features. Photodarkening in particular has proven useful for tuning resonances in photonic bandgap fibers [14], and we have further shown that this effect in As_2Se_3 microwires could lead to develop all-optical broadband fiber attenuators.

V. Conclusions

We have demonstrated the first all-optical variable, broadband attenuator based on an As_2Se_3 microwire. Tests for the 1550 nm and 1850 nm wavelength bands showed its functionality over a wide spectral range. Transient photodarkening effects in the ChG core of the microwire provide an effective means for varying the attenuation coefficient through adjustments of the power of the irradiating bandgap light. Furthermore, the photoinduced attenuation can also be modulated upon turning the bandgap light on and off. As_2Se_3 microwires can thus provide an attractive option for realizing all-fiber, all-optical modulators.

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