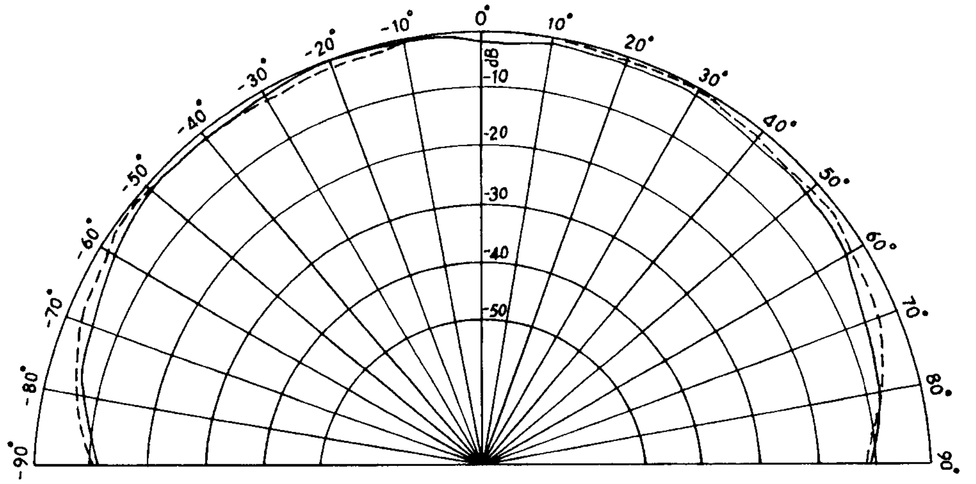

**Figure 4** Measured E-plane radiation patterns (solid line, square patch with three rings of separation 1 mm and shorted to ground; dashed line, square patch without any ring)

of 18% is achieved. For impedance matching, a quarter-wave transformer may be used by producing a gap through the rings, and because the rings are not fed directly, appreciable change in broadband nature of the antenna is not expected. The addition of these rings does not change the radiation pattern of the square patch.

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# DYNAMICS OF THERMALLY INDUCED OPTICAL NONLINEARITY IN GaSe THIN SLABS

**M. A. Hernández, E. A. Navarro, M. V. Andrés, A. Segura, and V. Muñoz**
Departamento de Física Aplicada
Universidad de Valencia
Dr. Moliner 50
46100 Burjasot, Valencia, Spain

**KEY TERMS**
*Optical nonlinearity, interference filters, nonlinear optics*

**ABSTRACT**
*A study of the nonlinear effects shown by thin slabs of GaSe metaled with Au is presented. A mathematical model is introduced to explain these thermally induced nonlinear effects. A rigorous solution is obtained for the steady state and a numerical procedure is introduced to obtain the time-domain behavior. Measurements of transient phenomena and steady state are analyzed and are found to be in good agreement with the theoretical predictions. © 1996 John Wiley & Sons, Inc.*

## 1. INTRODUCTION

Optical nonlinearities and bistability in GaSe-based interference filters have been the subject of study for several groups [1–4]. Our particular interest is on the study of thermally induced optical nonlinearity. When a laser beam impinges perpendicularly to the Au/GaSe/Au slab, the refractive index and absorption coefficient show changes [5–8], and the GaSe sample behaves like an interferometer with the possibility of nonlinear response. These nonlinear effects are important because they allow reproduction of the operation modes of electronic devices by purely optical means (switching, amplification, memory, logical operations, etc.).

In References [9–11] a GaSe layered crystal is presented as a new light modulator with very short switching times [10] and a large shift of absorption edge [11]. In the present article we show a theoretical and experimental study of these switching times and we present the evolution of these times as a function of the temperature and the voltage applied to the sample.

We choose this semiconductor because it has very suitable characteristics for nonlinear devices. Its bandgap of about 2.0 eV at room temperature [5] makes the GaSe an interesting material for nonlinear optical devices at 633 nm (the He-Ne laser light). Moreover, because of the electronic structure of the material, it is very easy to obtain thin samples from the ingot with a razor blade [12]. In Section 2 we show the theoretical model that we carry out in order to analyze the Au/GaSe/Au sample response. This model combines optical absorption, photoconductivity, and Joule's effect. Section 3 compares the model results and experimental observations in the GaSe semiconductor.

last group of measurements a pulse of voltage was applied to the device with a constant incident power $P_i$, and the evolution of the switching time for several temperatures and voltages was analyzed. The switching time is obtained as the time increment from the moment in which the transmitted power is 10% of the maximum power up to the instant in which the transmitted power is 90% of the maximum transmitted power. Figure 2 shows a series of measurements of the first group. Figure 2 shows how the nonlinear response varies with the applied voltage; the temperature in the sample was 49 °C. Because of the characteristics of the device in the given range of $P_i$, we get a nonlinear response but not a bistable response. Nevertheless some interesting features can be observed. That is, when the incident power is not very high the response is linear, and its slope decreases with the voltage. The same phenomenon is observed at other temperatures.

On the other hand, when the $P_i$ is higher, we arrive at a state where the response is no longer linear. In this part we observe the effects of the heat absorption and the feedback caused by changes in the optical properties of the GaSe (refraction index and absorption coefficient). This is because the refraction index or absorption coefficient increases, the power absorption in the GaSe also increases, and the temperature in the device runs parallel to this increment. Figure 2 also shows the theoretical response provided by the model for the steady state (Section 2.1). We contrast the response for 0, 8, and 10 V, at a room temperature of 49 °C. After that we apply the dynamical model of Section 2.2 to predict the nonlinear response for different Au/GaSe/Au samples for different voltages and boundary conditions. This is shown in Figure 3. The implemented code for the transient analysis allows us to design the Au/GaSe/Au sample in order to obtain a bistable response.

In the second and third group of measurements we studied the dependence of the switching time with the temperature and the applied voltage. Figure 4 shows a series of measurements for 49 °C and different applied voltages when a pulse of power of 35 mW is incident. All of them show a maximum peak of transmission when the laser light is applied and turned on, and a later evolution toward a steady value. When the absorbed power equals the dissipated power the transmission remains constant. The switching time was deduced through these measurements and its evolution was

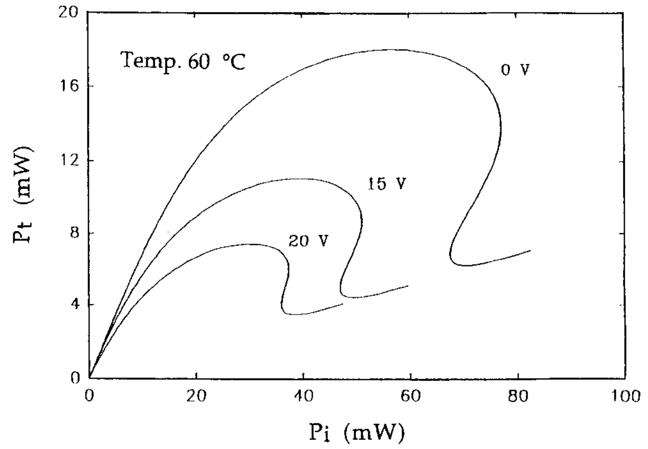

**Figure 3** Theoretical prediction for the nonlinear response for different applied voltages

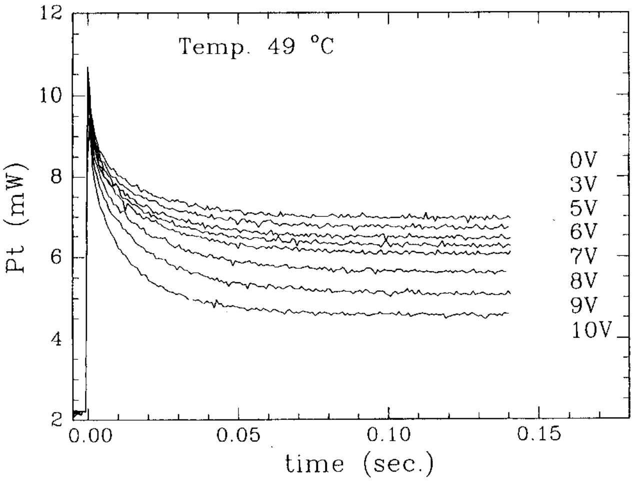

**Figure 4** Transmitted power versus time for different applied voltages. Incident power is a square pulse in the time domain

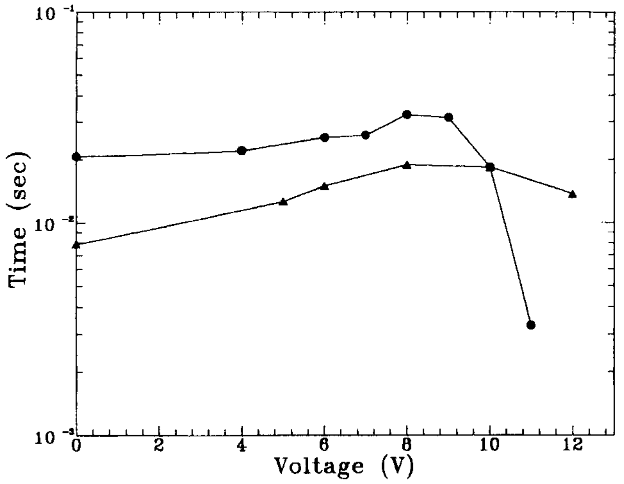

**Figure 5** Switching time: triangles, theory; circles, experiment

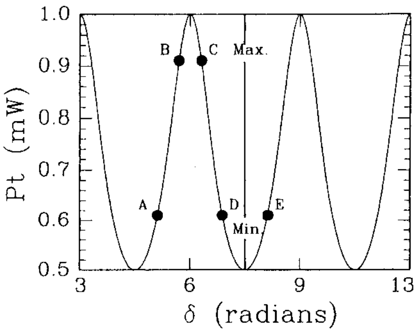

**Figure 6** Transmittance in a Fabry-Perot interferometer

studied. Figure 5 shows the measured time and the results obtained from the simulation. We observed a constant time for low voltages and a threshold voltage; from this value of the voltage there is an increase in the switching time followed by a continuous decrease until orders of milliseconds.

The switching-time evolution with the voltage is not temperature independent. It is possible to obtain three different evolutions. The origin of this is the Au/GaSe/Au behavior as a Fabry-Perot, and for that reason the transmittance and absorbance functions of the Fabry-Perot (see Figure 6) interferometers. In this interferometer maximum and minimum points of transmittance and absorbance are defined by the Airy function, and in both transmittance and absorbance functions maximum and minimum, respectively, appear for the same values of phase in the Airy function. The different evolutions are due to the constitutive parameters of the device. The three switching-time evolutions are (a) a constant value until a given voltage and after this a continuous decreasing; this happens when the device is close to a maximum of transmittance on the right (point C in Figure 6); (b) a constant value until a given voltage and a continuous increase; in this case the device is close to a maximum on the left (point B in Figure 6); and the third case; (c) corresponds to point D in Figure 6; the device is close to a minimum on the left. The switching-time evolution of our physical Au/GaSe/Au device agrees with the last case.

The last group of measurements were taken for a constant incident power and a pulse of applied voltage. In this way we try to control the transmittance with the voltage. A group of data were recorded in which we observe how the modulation of transmittance increases with the applied voltage. Two features are clearly shown. The first is that this modulation is not linear with the voltage [see Figures 7(a) and 7(b)], which can be explained due to thermal effects of heat absorption generated by Joule's effect in the device. We can see in Eq. (3) that this heat is proportional to $V^2$. The second important feature is that from a given voltage, 12 V in our case, the modulation is no longer increased. This is because from a given temperature the absorption coefficient behaves as a constant [7].

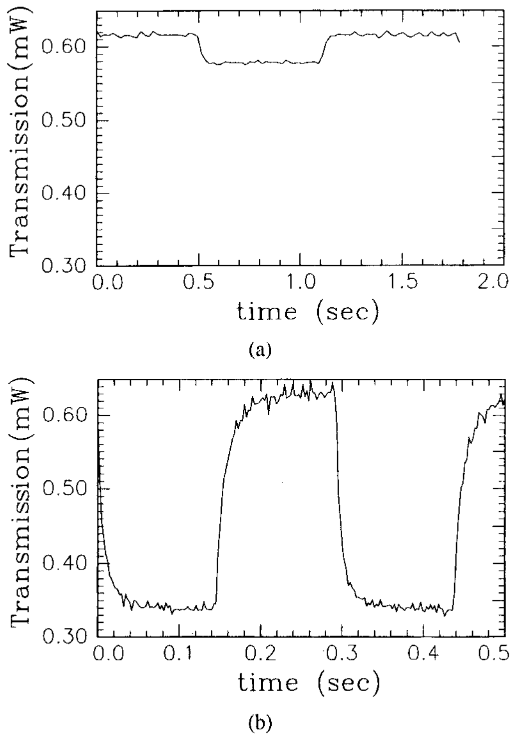

**Figure 7** Transmitted power versus time for two different applied voltages: (a) 6 V, (b) 12 V. The incident power is 35 mW

## 4. CONCLUSIONS

In this work we show how the semiconductor GaSe can be used as a power controller modulated by voltage. We present a theoretical model that describes the nonlinear optical characteristics observed as a function of the thermal effects. A direct solution is presented for the steady state, and a numerical procedure is introduced to solve the model in the time domain. Both the changes in refractive index and absorption coefficient are very important to explain the Au/GaSe/Au behavior.

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