QIRT10
http://dx.doi.org/10.21611/qirt.2010.082
10th International Conference on Quantitative InfraRed Thermography
July 27-30, 2010, Québec (Canada)

Free carrier diffusion-wave modulation of a sub-bandgap cw laser beam

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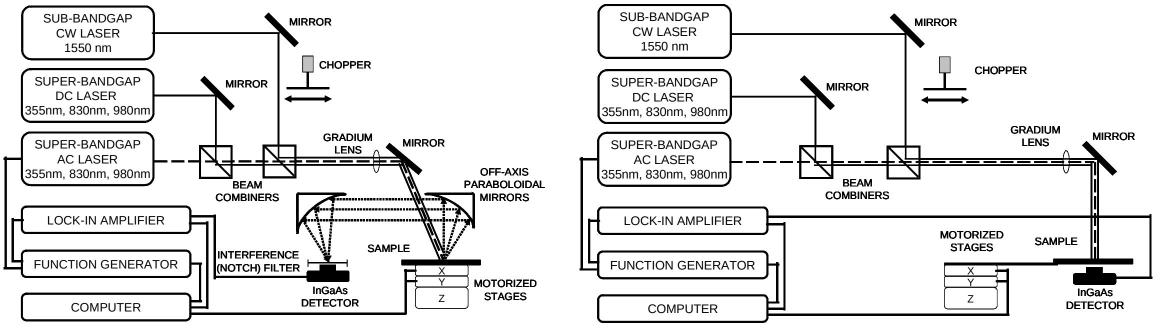
Nowadays the use of excited free carriers in semiconductors for light modulation and switching is becoming increasingly popular because of speed, absence of moving components, negligible parasitic heating, no effects from external fields and no electrical, thermal or acoustic influences on the modulating/switching active area. In this work we describe the modulation of an unmodulated *(cw)* 1550-nm sub-bandgap laser beam with power P_{cw}, by the spatially dependent absorption coefficient of free carriers created in semiconductor medium following absorption of a super-bandgap laser radiation. The semiconductor medium were one and two-side polished Silicon wafers. As a super-bandgap radiation were used two collinear laser beams, one harmonically modulated *(ac)* at angular frequency ω with power $P_{ac}(t)$ and other unmodulated *(dc)* with power P_{dc},, both with different combinations of the wavelengths 355 nm, 830 nm, and 980 nm. When the super-bandgap beams $P_{ac}(t)$ and P_{dc}, are off the sub-bandgap laser absorption coefficient is due to residual (background) absorption and has a small value: $a_{cw} = a_0$. When $P_{ac}(t)$ and P_{dc}, are on, their radiation is strongly absorbed within a thin surface layer of the material and inter-band photocarrier excitation occurs. The time-dependent absorption coefficient of the sub-bandgap radiation can be expressed as:

$$\alpha_{cw}(z,t)=\alpha_0+\alpha_{fc}(z)+\frac{1}{2}\alpha_{fc}(z,\omega)\left(1+e^{i\omega t}\right) \qquad (1)$$

Here a_{fc} is the free-carrier absorption coefficient at the sub-bandgap beam wavelength and it is function of the excess free carrier density $\Delta N(z,\omega)$ generated by the *(dc)* and *(ac)* superband-gap laser beams. The subband-gap laser radiation absorptance, $A_{cw}(\omega,t)$, defined as the absorption coefficient multiplied by the total thickness L of the semiconductor, can be written as:

$$\begin{aligned} A_{cw}(\omega,t) &= \alpha_0 L+\int_0^L \alpha_{fc}(z)\,dz+\frac{1}{2}\left(1+e^{i\omega t}\right)\int_0^L \alpha_{fc}(z,\omega)\,dz = \\ &= \alpha_0 L + C\left(\int_0^L \Delta N(z)\,dz+\frac{1}{2}\left(1+e^{i\omega t}\right)\int_0^L \Delta N(z,\omega)\,dz\right) \qquad (2) \end{aligned}$$

where C is a sub-bandgap laser radiation wavelength depending constant.



a b

***Fig. 1**. Experimental setups. (a) reflected and (b) transmitted sub-bandgap ac power $P_{cw}(\omega,t)$.*

Modulated sub-bandgap radiation $P_{cw}(\omega,t)$ is generated by the time-dependent absorptance $A_{cw}(\omega,t)$. If neglect the infinite inter-reflections of the sub-bandgap laser radiation from the semiconductor top and bottom surfaces it can be shown that:

http://dx.doi.org/10.21611/qirt.2010.082

$$P_{cw}\left(\omega,t\right)=P_{cw}T_0 e^{-\left(\alpha_0 L+CT_1\int_0^L \Delta N\left(z\right)dz\right)}\left[1-\frac{1}{2}m(\omega)\left(1+e^{i\omega t}\right)\right] \tag{3}$$

where:

$$m\left(\omega\right)\equiv CT_2\int_0^L \Delta N\left(z,\omega\right)dz \tag{4}$$

Here *m(ω)* is the modulation depth of the optoelectronic modulator and T_0, T_1 and T_2 are terms involving the absorption, reflection and transmission coefficient of the semiconductor at the wavelength of the subband-gap laser.

Two groups of experiments were performed on the experimental setups presented on **Figure 1**. In the first group the free carrier generated sub-bandgap ac power $P_{cw}(\omega,t)$ was reflected from the rough back surface of the one-side polished wafer. To minimize the contribution from synchronously emitted photo-carrier radiometric (PCR) power contributions, $P_{PCR}(\omega,t)$, as well as from back scattered sources power, $P_{ac}(t)$ and P_{dc}, to the modulated back propagated sub-bandgap power, an interference filter was positioned in front of the InGaAs photodetector, transmitting the 1550 nm radiation only. In the second group of experiments, $P_{cw}(\omega,t)$ was transmitted through the two-side polished wafer and the transmitted modulated sub-bandgap power was monitored. In this case any $P_{ac}(t)$ and P_{dc}, were eliminated through absorption near the top (front) surface of the wafer. The presence of PCR signal power was negligible. In the both groups of experiments the photodetector signal was proportional to *m(ω)*, Eq. (4).

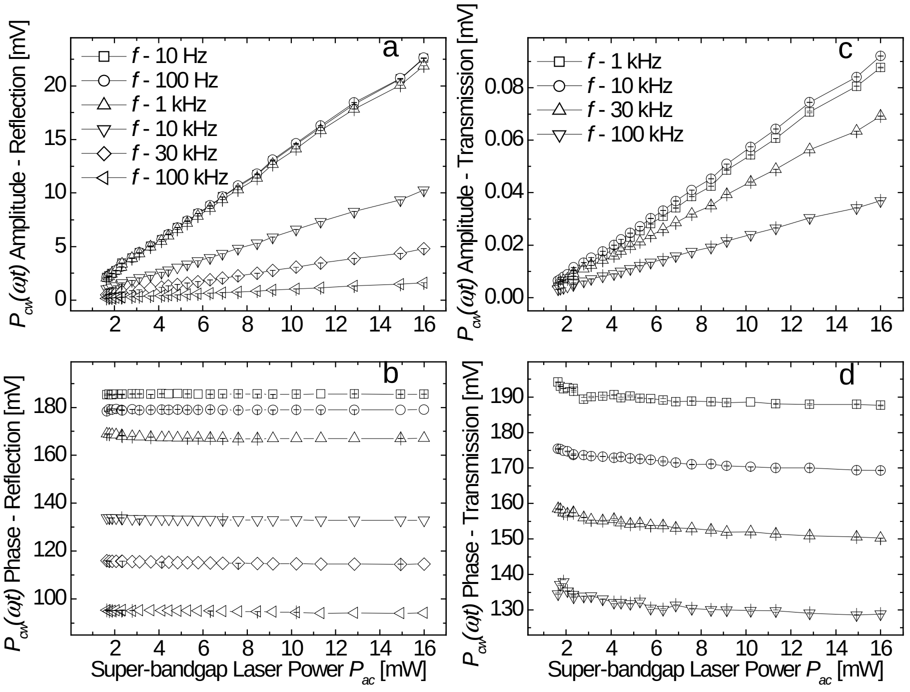


***Fig. 2**. Free-carrier modulation super-bandgap laser power $P_{ac}(t)$ light scan; $P_{dc} = 0$. (a) and (b) amplitude and phase-reflection (back-propagation) modulation; (c) and (d) amplitude and phase–transmission modulation.*

To determine the reference value for the optoelectronic modulator, the modulated signal corresponding to *m(ω)* = 1 or 100% modulation of P_{cw}, the super-bandgap laser radiations $P_{ac}(t)$ and P_{dc}, were turned off, and P_{cw} was modulated with a mechanical chopper at 1 kHz. These reference measurements were made in both groups of experiments without changing the relative positions of the photodetector, wafer and P_{cw} laser beam. **Figures 2a** and **2b** show the amplitude and phase of back propagated $P_{cw}(\omega,t)$ from the rough back surface of one-side polished wafer for six different frequencies. The free-carrier modulation depth of $P_{cw}(\omega,t)$ obtained using $P_{ac}(t)$ at 16 mW and $P_{dc} = 0$ at 1 kHz relative to 100% modulation of the sub-bandgap beam by the mechanical chopper was found to be 3.4%. **Figures 2c** and **2d** show the amplitude and phase of transmitted $P_{cw}(\omega,t)$ through the two-side polished wafer for four different frequencies. Using the same modulation depth reference procedure as for one side polished wafer, it was found that the modulation depth of P_{cw} was only 0.36%.

Based on the presented theoretical and experimental evidence, there are excellent prospects for further improvement of this optical driven modulation method to produce modulating/switching devices for use with the modern photonic technologies.