Semiconductor saturable absorber mirror structures with low saturation fluence

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ABSTRACT We present two novel semiconductor saturable absorber mirror (SESAM) designs which can exhibit more than ten times lower saturation fluence than classical SESAM devices. Design considerations and characterization data are presented. These devices are particularly suited for passively mode-locked lasers with ultra-high repetition rates.

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1 Introduction and motivation

Semiconductor saturable absorber mirrors (SESAM devices) [1, 2] are well established for passive mode locking or Q-switching of many kinds of solid-state lasers [3–5]. Since both linear and nonlinear optical properties of these devices can be engineered over a wide range, the device performance can be readily optimized for a wide variety of laser designs and operating regimes. The main device parameters such as operation wavelength λ, modulation depth ΔR, saturation fluence Fsat, and absorber recovery time τa can be custom designed in a wide range for stable continuous-wave (cw) mode locking [6], pure Q-switching [7], or a combination of both [3].

One important limit of a SESAM device is its saturation fluence, which has typical values in the range of several tens to hundreds of μJ/cm². Lower saturation fluence is particularly relevant for fundamentally mode-locked solid-state lasers with an ultra-high pulse-repetition rate (i.e. > 1 GHz) [8–10]. It becomes harder to saturate the SESAM device in such a laser, as the intracavity pulse energy becomes increasingly lower, requiring laser mode sizes on the SESAM device on the order of only a few microns (i.e. close to the diffraction limit). Additionally, the very short cavity length required for such high repetition rates does not leave much room for a cavity design with arbitrarily small mode sizes on the SESAM device. Furthermore, the threshold for continuous-wave mode locking without Q-switching instabilities (QML threshold) is decreased with a low saturation fluence [6]. It is also worth noting that passively mode-locked vertical external cavity semiconductor lasers (VECSELs) can also benefit from a SESAM device with low saturation fluence [11, 12].

Novel absorber materials with increased absorption cross sections are one alternative to reduce the saturation fluence. Quantum dots are promising candidates for this [12, 13], and have shown the potential. For example, a p-type material could be used to realize a quantum-well superlattice, with the cavity length adjusted for resonance, i.e. the intensity in the cavity would be much higher than the incident intensity. Such devices are well suited for high-contrast optical switching. The first SESAM device for solid-state lasers, the anti-resonant Fabry–Perot saturable absorber, consisted of a Fabry–Perot cavity filled with a saturable absorber, and with its thickness adjusted for anti-resonance, i.e. the intensity in the cavity was substantially lower than the incident intensity [1]. Later, we recognized that the top mirror element was not necessary, and that the absorber could be integrated in the lower Bragg mirror [18, 19] or an appropriate spacer layer [2, 19]. Earlier, a nonlinear Bragg reflector was introduced by Garmire’s group but had too much loss modulation to be suitable for passively mode locking solid-state lasers at the time [20]. A close-to-resonant Fabry–Perot saturable absorber structure, referred to as the D-SAM (dispersive saturable absorber mirror) was used to optimize both negative group-delay dispersion (GDD) and the nonlinear modulation to construct more compact femtosecond sources [21].

Here, we discuss two new structures which allow for tailoring of the device’s saturation fluence and GDD as well as the modulation depth. We choose our design wavelength to
be 1314 nm, motivated by the work in the second telecom window with Nd:YLF lasers. However, the concepts and arguments hold for arbitrary wavelengths. For clarity, we begin our explanation with an illustration of the field intensity in a ‘standard’ DBR.

2 DBR structure and field intensity enhancement factor $\xi$

Figure 1 shows the layer structure and field intensity near the top of the structure (this and all further field structures are calculated using a transfer-matrix formalism). In this case, our DBR consists of 30 pairs of alternating quarter-wave layers of AlAs as low-index material ($n = 2.91$ at 1314 nm; quarter-wave layer thickness 112.9 nm) and GaAs as high-index material ($n = 3.41$ at 1314 nm; quarter-wave layer thickness 96.3 nm). Incoming light with intensity normalized to 1 creates a standing wave pattern in this structure. In this definition, the peak of the field intensity (square of the envelope of the electric field) of the resulting standing wave pattern is 4 outside the device, assuming a mirror that has a reflectivity of 100% and negligible loss. We define the enhancement factor $\xi$ as the maximum field intensity in the structure relative to 1 (i.e. relative to the incoming field intensity).

In the DBR example, no absorber layer is shown. In order to introduce saturable absorption (nonlinear reflectivity), an absorber layer would typically be positioned at or very near the maximum standing wave peak inside the structure (resulting in lowest saturation fluence for the device). When a thin absorber layer is added, we can make the assumption that the absorption plays a negligible role in the field distribution, as long as the total absorption is small, i.e. on the order of a few percent. Similarly, any change in index of the thin absorber layer has negligible impact on the field distribution, since reflections from the individual surfaces nearly cancel out due to destructive interference. The expected modulation depth of the device with absorber layer is then directly proportional to $\xi$, and the saturation fluence inversely proportional to $\xi$ [22], for a given absorber layer thickness and material.

Considering the field intensity in this ‘standard’ DBR, we see in Fig. 2 that the $\xi$ factor is approximately 0.34, and the GDD and $\xi$ are nearly flat over the center-wavelength range. This device does not exhibit any resonant-like behavior in either the field intensity or the GDD. Note that we can make the following comments on this DBR structure: the last quarter-wave layer is a high-index layer, and accordingly the field intensity at the air interface ends on or very near a node (i.e. a field null).

Now consider a DBR structure with an additional quarter-wave layer of low-index material placed on top of the structure (Fig. 3). This results in several key feature changes to the field intensity in the structure and the device’s GDD behavior (Fig. 4). First, the $\xi$ factor now equals 4, i.e. it is enhanced with respect to the ‘standard’ DBR by a factor of more than 11. Secondly, the device exhibits some peaking of the group delay, resulting in significant GDD in the device away from its design-operating point. This peaking of the group delay is ‘resonant-like’ behavior. However, the field intensity in the device is never larger than the external intensity. Also note that the air–device interface characteristically ends on or near a peak (anti-node) of the field intensity.

Note that we have chosen to add a quarter-wave layer of the low-index material of the DBR. However, we are free to add a quarter-wave layer of any index material, and still achieve similar results, i.e. an increase of the $\xi$ factor to nearly 4, and an enhanced GDD response. A higher-index layer results in more peak GDD, and a lower-index layer results in less peak GDD.