# 220-fs erbium-ytterbium:glass laser mode locked by a broadband low-loss silicon/germanium saturable absorber

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We demonstrate femtosecond performance of an ultrabroadband high-index-contrast saturable Bragg reflector consisting of a silicon/silicon dioxide/germanium structure that is fully compatible with CMOS processing. This device offers a reflectivity bandwidth of over 700 nm and subpicosecond recovery time of the saturable loss. It is used to achieve mode locking of an Er-Yb:glass laser centered at 1540 nm, generating 220-fs pulses, with what is to our knowledge the broadest output spectrum to date. 

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Passive mode locking with a saturable Bragg reflector (SBR) is a powerful method of generating a steady stream of picosecond or femtosecond pulses from a laser.[1,2] To date, SBRs have been fabricated as both bulk and quantum-well devices from III–V compound semiconductor materials that are not compatible with the silicon material platform. In contrast the silicon/germanium SBR (Si/Ge-SBR) demonstrated here consists of a CMOS-compatible silicon/silicon-dioxide ($Si/SiO_2$) Bragg reflector and a Ge saturable absorber layer (Fig. 1a). Because of the high-refractive-index contrast ($n_{SiO_2} = 1.45$ and $n_{Si} = 3.5$), only six layer pairs in the Bragg mirror are sufficient to achieve a maximum reflectivity of 99.8%. On top of the $Si/SiO_2$ Bragg stack, a Ge saturable absorber layer is embedded in a Si layer of $3\lambda/4$ optical thickness at the center wavelength of 1400 nm. This layer resides at a peak of the standing-wave pattern of the electric field to maximize absorption and minimize saturation intensity (Fig. 1a).

The manufacturing of the SBR was aimed at achieving both high reflectivity of the Bragg mirror and a sufficiently strong nonlinear response of the absorber layer for mode locking of an Er-Yb:glass laser. We fabricated the six-pair reflector by repeating poly-Si deposition and thermal oxidation using a silicon-on-insulator (SOI) wafer as the starting material (Fig. 1b, step 1). Then the Bragg mirror was bonded with a new Si substrate (Fig. 1b, step 2). The Si handle and the buried oxide of the SOI wafer were chemically etched to expose the crystalline Si layer of the SOI wafer for successive Ge epitaxial growth (Fig. 1b, step 3). A 40-nm-thick Ge saturable absorber layer was deposited by the ultrahigh-vacuum chemical-vapor deposition technique developed by Luan *et al.*[3] (Fig. 1b, step 4). Finally, a thin oxide was grown on Ge as a passivation layer and a poly-Si cap layer was deposited. The manufacturing process, including bonding of a new substrate and removal of the original one, resulted in reversal of the $Si/SiO_2$ layer sequence of the reflector with respect to layer growth. Thus the layers of lowest surface roughness—those that were grown first—end up topmost in the mirror, exposed to the highest electric field strength, whereas the rougher layers, which were grown last, are buried

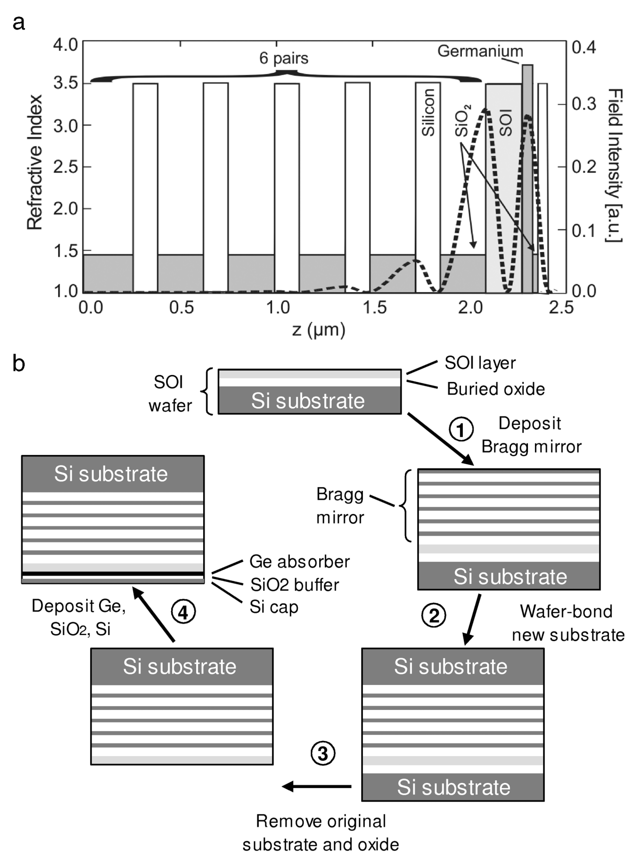


Fig. 1. Structure and fabrication process of the Si/Ge-SBR. a, Refractive-index profile and standing-wave pattern (dashed curve) of the Si/Ge-SBR. b, Illustration of the device fabrication, resulting in a reversal of the $Si/SiO_2$ layer sequence.

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deep in the mirror (Fig. 1a). This reversal of the layer sequence significantly reduces surface roughness and scattering losses, leading to an unprecedented 99%-reflectivity bandwidth of 700 nm (Fig. 2b). Furthermore, substrate reversal terminates the reflector with the crystalline Si layer of the SOI wafer rather than with polycrystalline material deposited on a Bragg mirror. It is the crystalline nature of this Si layer that preserves the optical absorption properties of the Ge layer to achieve saturable absorption in the material system at 1550 nm.

The nonlinear response of the device was characterized in a series of pump–probe measurements with 150-fs pulses centered at 1540 nm from an optical parametric oscillator. For low to medium fluence values (e.g., 40 $\mu J/cm^2$), the Ge layer acts as a fast saturable absorber with up to 0.13% of modulation depth (Fig. 2a). We observe subpicosecond recovery of the bleaching, with the temporal resolution of our measurement being limited by the pump and probe pulse durations. We attribute the fast relaxation process to intervalley scattering within the conduction band. In contrast, for high fluences (e.g., 300 $\mu J/cm^2$), carriers generated by two-photon absorption induce free-carrier absorption and turn the Ge layer to an inverse saturable absorber. The strong inverse saturable absorption of the Si/Ge-SBR is due to the two-photon absorption in the Ge layer ($\beta_{Ge, 1500nm} = 300$ cm/GW), which is much greater than that of Si or GaAs. The observed behavior leads to dual functionality of the Si/Ge-SBR in a mode-locked laser: (i) the fast recovery permits ultrashort pulse generation, (ii) onset of inverse saturable absorption at high fluences helps stabilize high-repetition-rate lasers against $Q$ switching by limiting the maximum intracavity power.[4,5] This instability has prevented successful mode-locked operation of lasers with long upper-state lifetimes and high repetition rates until recently[6,7] and is a major obstacle for compact laser integration. The thin Ge layer grown on silicon is compressively strained, leading to a shift of the bandgap by 38 nm to shorter wavelengths. As a result, absorption of the Ge sets in at 1580 nm (Fig. 2b), leading to a total loss of 0.3% and a nonsaturable loss of 0.17% at the laser wavelength, as determined by comparison of the intracavity power obtained with the Si/Ge-SBR with different output couplers. In addition, a transmission electron micrograph revealed a small error in the SOI-layer thickness, placing the Ge-absorber layer slightly off the peak of the electric field. A larger modulation depth of the SBR can be expected from a precise positioning of the Ge layer at a field maximum, as well as from the use of a thicker layer. From pump–probe measurements we estimate the saturation fluence to be ~30 $\mu J/cm^2$.

The fast recovery time of the Si/Ge-SBR combined with its high reflectivity leads to superior spectral width and pulse duration of the bulk Er-Yb:glass laser mode locked with this device. A phosphate glass, Kigre QX/Er, served as the gain medium in the laser. It is flat Brewster polished, placed at one end of the four-element laser cavity (Fig. 3a), and its flat side serves as an output coupler with 99.8% reflectivity. The laser is pumped with a 450-mW fiber-coupled diode laser (Bookham, type G07). The overall intracavity loss is minimized with highly reflecting mirrors, low output coupling, and a highly reflecting Si/Ge-SBR, leading to an average intracavity power of 8.7 W. The laser is operated with a highly saturated gain resulting in a flat gain profile to support a broad optical spectrum.[8] We obtain an optical spectrum centered at 1550 nm with a FWHM bandwidth of 11 nm and covering the entire $C$ band of optical communications at approximately the −10-dB level (Fig. 3b). After dechirping the pulses extracavity with 1.0 m of single-mode fiber (Corning SMF-28), the inferred pulse duration from the intensity autocorrelation is 212 fs (Fig. 3d). Phase retrieval with an iterative algorithm[9] reveals a pulse width of 220 fs, which is 10% larger than the transform-limited value obtained from the zero-phase Fourier transform of the power spectrum. To our knowledge, these are the shortest pulses generated from a bulk Er-Yb:glass laser to date,[10] and approximately an order of magnitude shorter than those obtained solely from mode locking of an Er-Yb:glass laser with a SBR.[11] The laser operates at a 169-MHz repetition rate with a clean rf spectrum and a noise floor more than 70 dB below the signal level (Fig. 3c). No $Q$-switching behavior was observed, regardless of pump-power level despite the long upper-state lifetime and the small emission cross section of the gain medium. We attribute the high stability against $Q$ switching to the

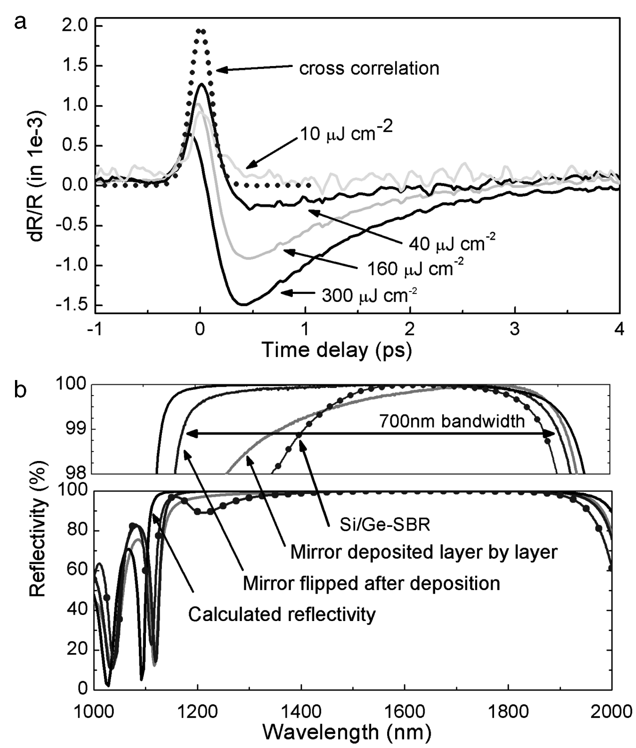


Fig. 2. Measured properties of the Si/Ge-SBR. a, Pump–probe traces of the Si/Ge-SBR taken at various fluence values (solid curves) along with the cross correlation of the pump–probe laser source (dotted curve). b, Measured and calculated reflectivity of the six-pair $Si/SiO_2$ Bragg mirror with and without the Ge layer.

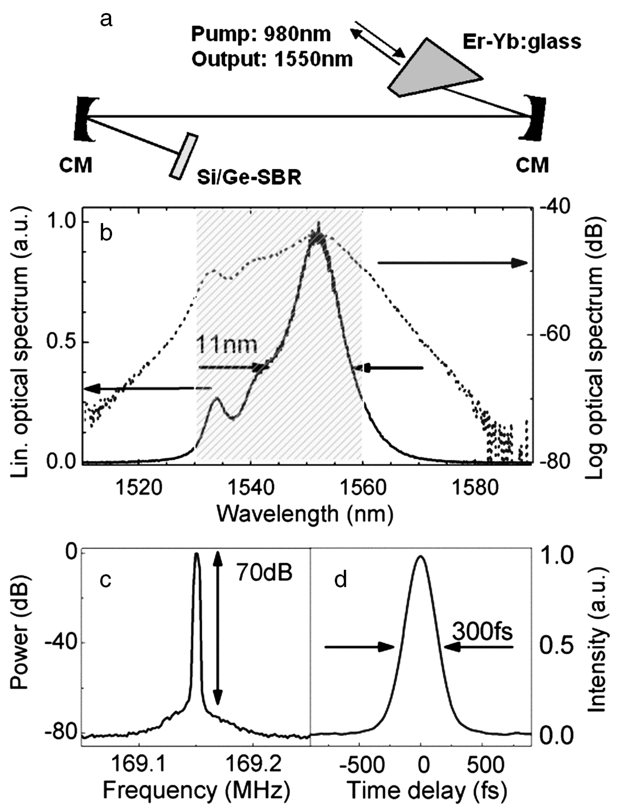


Fig. 3. Setup and performance of the Er-Yb:glass laser. a, Schematic of the laser cavity (CM, curved mirror). b, Optical spectrum of the Er-Yb:glass laser mode-locked with the Si/Ge-SBR on linear and logarithmic scales. The *C* band of optical communications is indicated by the cross-hatched region. c, rf spectrum of the laser. d, Background-free intensity autocorrelation of the dechirped pulse train.

inverse saturable absorption in the Si/Ge-SBR at high fluence.

In conclusion, we have demonstrated a silicon/germanium saturable Bragg reflector fabricated with a CMOS-compatible process. Its nonlinear response has been characterized by femtosecond pump–probe measurements showing fast saturable-absorber behavior on a femtosecond time scale and strong inverse saturable absorption at large fluence values. The device has been used to attain self-starting operation of a passively mode-locked Er-Yb:glass laser with an optical spectrum covering the entire *C* band of optical communications. The larger modulation depth of the present device at shorter wavelengths with the broad bandwidth of the $Si/SiO_2$ backmirror can be utilized in mode locking other laser systems, such as Cr:forsterite and $Cr^{4+}$:YAG, which support few-cycle laser pulses. The development of a saturable absorber in the silicon material platform paves the way for construction of chip-scale mode-locked lasers in the near future. We expect that such lasers will become compact, low-noise, inexpensive light sources that allow for new applications in optical communications,[12] high-speed optical sampling,[13] on-chip clocks,[14] and low-noise microwave oscillators.[15]

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