A narrowband thermal emitter exhibits higher energy efficiency and sensitivity in molecule sensing and other mid-infrared (MIR) spectral range applications compared to a blackbody emitter. Most narrowband thermal emitters involving surface plasmons have a relatively low quality factor ($Q$-factor) and require complex fabrication processes. Here we propose a bilayer cavity-enhanced Tamm plasmon (TP) structure with a high/low refractive index bilayer sandwiched between a metal and distributed Bragg reflector (DBR) to achieve an enhanced $Q$-factor and maintain higher emittance over a conventional pure DBR-metal TP structure-based emitters. The large optical thickness of the high/low index bilayer cavity aids in increasing the $Q$-factor ($\sim 172$ for emission) of the cavity resonance. Furthermore, a tunable $Q$-factor is achieved ($Q$ from 172 to 47 for emission) by incorporating phase-changing material $\text{Ge}_2\text{Sb}_2\text{Te}_5$. This easy-to-fabricate and tunable high $Q$-factor emitter is competent as a narrowband MIR light source in molecule sensing, typically gas sensing applications. © 2018 Optical Society of America

https://doi.org/10.1364/OL.43.005230

Infrared thermal emitters with specially designed nanostructures to engineer the emission spectrum region are used for a variety of applications, including gas sensing [1–4] and thermophotovoltaic power generation [5–7]. Aimed for these applications, emitters with optimized narrowband emission are of vital importance. In conventional nondispersive infrared (NDIR) sensing [8], a broadband thermal emitter (such as a micro-bulbs) is used as the source, and there are two filters to pick up the emission required for sensing. Since the absorption linewidths of most target chemical substances are narrow, a large proportion of out-of-band emission is wasted. To better distinguish the absorption peak of the target from other adjacent peaks, the filters should also be critically designed with narrowband transmittance [2]. However, realizing a large-area narrowband emitter that eludes the disadvantages of the emitter part in a conventional NDIR system and easy fabrication remains challenging, and most demonstrated narrowband emitters are not tunable with nonvolatility.

One of the approaches to achieve narrowband thermal emission is to prepare metallic nanostructures such as photonic crystals [9,10] or a metal-insulator-metal (MIM) structure where the optical resonant modes are highly confined between two metal layers [11,12]. However, this kind of emitters bring broadened emission peaks because of strong free-carrier absorption by metals (experimentally, $Q < 30$), which is inevitable in mid-infrared (MIR) wavelength regime. The grating-based emitter has also been demonstrated with an experimental quality factor ($Q$-factor) of 460 with a peak emissivity of 0.17 [13]. An ultra-narrowband ($Q \sim 200$) electrically tunable thermal emitter combining quantum wells and photonic crystal slabs has been investigated [14–16]. Since these thermal emitters involve a complicated fabrication process, it is highly expensive and difficult to realize a large-area narrowband thermal emitter of this kind.

Achieving high $Q$-factor thermal emitter with a large area and lithography-free fabrication has attracted great attention in recent years [17,18]. Multilayer thermal emitters fabricated with a simple deposition process have been demonstrated, and it is also reported that high $Q$-factor Tamm plasmon (TP) resonance is the key for producing narrowband emission for most designed emitters [19]. Typical designs of Tamm plasmon structures use metal-side structures (incident light from thin metal film) which need an optimized metal thickness [20–22]. Since the decay of the electric field inside a metal layer is very fast for the MIR wavelength regime, a metal-side design calls for an ultrathin top metallic layer, and the bandwidth can hardly be controlled. Thus, a distributed Bragg reflector (DBR) side structure (incident light from a DBR) is developed, since the magnitude of absorptivity and $Q$-factor can be determined by the periods of DBR pairs, which helps reduce the difficulties for fabrication and mechanical stability. However, these multi-layer structures provide narrowband emission at fixed peak wavelengths and can hardly be used for multi-compound sensing [23,24]. Alternatively, tunability can be attained by...
utilizing advanced materials such as phase-changing materials (such as VO₂ [25] and Ge₂Sb₂Te₅ [GST] [26–28]) whose permittivity can be tuned by changing their phases. Among these phase-changing materials, GST has unique optical properties in the mid-infrared region—amorphous GST (aGST) is a lossless dielectric, and crystalline GST (cGST) is a low-lossy dielectric—generating avenues to achieve tunable narrowband thermal emitters.

In this Letter, we demonstrate the combination of a DBR side Tamm plasmon structure with a phase-changing material GST to realize a narrowband and Q-factor tunable MIR thermal emitter. The emitter has two major distinct features. (1) A bilayer cavity between a DBR and a gold film is used to trap light at the resonance wavelength. Thereafter, the coupling of the TP mode and cavity mode brings a stricter condition for the coupled mode, resulting in a narrowband emission without sacrificing emittance. (2) A tunable Q-factor for the narrowband emission peak is realized with the phase-changing material GST. The Q-factor can be tuned without significantly varying the emission peak wavelength and emittance. For gas sensing applications, the spectral linewidths of gas molecules increase with higher temperature or high pressure due to Doppler broadening, collision broadening, and other effects [29].

A schematic diagram of the designed emitter consisting of a Ge/ZnS bilayer cavity sandwiched between gold film and a Ge/ZnS DBR is shown in Fig. 1(a). The DBR includes six alternating layers of Ge and ZnS with thicknesses 3λ/4n_H, respectively; λ is the target emission peak wavelength; n_L and n_H are refractive indices of Ge and ZnS at the peak wavelength, respectively. To achieve tunability, GST, instead of Ge, with an optical thickness of three quarters is chosen as the material for the top layer in a DBR. The high refractive index contrast between the high and low index layers (n_GST = 4.02, n_GST = 4.25, and n_ZnS = 2.25 at λ = 4.3μm) ensures high reflectance of the DBR at the target wavelength. Towards forming cavity resonant modes between gold films and the DBR, the thicknesses of the Ge and ZnS layers are set as λ/n_H and λ/2n_L, respectively.

The absorptance of a designed emitter for normal incidence is calculated with a transfer matrix method for both aGST and cGST cases and is shown in Fig. 1(b). The thicknesses of the GST, Ge, and ZnS layers are set for a target peak wavelength of 4.3μm in calculation, and gold layer is set to be 100 nm thick which is high enough to make it opaque for MIR light. The Q-factor and peak absorptance of the absorption peak (I) at 4.298μm are 491 and 0.84 for the aGST case, respectively. For the cGST case, Fano resonance occurs due to the coupling between resonance in the monolayer cGST and cavity-enhanced TP resonance. As shown in Figs. 1(c) and 1(d), the electric fields normalized with an incident field (calculated by COMSOL Multiphysics) for aGST (I: λ = 4.298μm) and cGST (II: λ = 4.285μm) layers are similar in terms of field distribution in the DBR layers and bilayers. Since the imaginary part of the refractive index for aGST is negligible at this wavelength range, the high absorptance at λ = 4.298μm corresponds to a high resistive loss of gold due to electric field enhancement near the gold surface. As for the cGST case, there is an additional intrinsic absorption in the cGST layer for its nonzero imaginary refractive index. At λ = 4.462μm, the absorption peak for a relatively wide absorption band locates. The field distribution in Fig. 1(d) shows the resonance in the cGST layer and low electric field intensity in the DBR layers and bilayers. Therefore, the high absorptance at λ = 4.462μm is mainly determined by the resonance in the cGST layer and intrinsic absorption of cGST. At the Fano dip (II: λ = 4.303μm), due to off-resonance in the monolayer cGST, the absorptance is relatively low.

The simulated absorptance spectrum of the bilayer cavity-enhanced TP structure is compared with the spectrum of a conventional DBR TP resonance structure and monolayer cavity-enhanced TP structure with a similar film thickness (gold film thickness is excluded) (Fig. 2). The thicknesses of the Ge layer (light blue layer in Fig. 2) and ZnS layer (gray layer) in the DBR of three different structures (DBR, DBR + monolayer, and DBR + bilayer) are set to be 3λ/4n_H and λ/4n_L, respectively; the thickness of the ZnS monolayer cavity is set to be λ/2n_L [Fig. 2(b)]; and the thicknesses of the Ge and ZnS in the bilayer are set to be λ/n_H and λ/2n_L, respectively [Fig. 2(c)]. To achieve high Q-factor of emitters, the reflectance of the DBR should be high enough to form a high Q-factor TP resonance, which can be realized by adding high/low index alternating layers of the DBR. On the other hand, high reflectance due to high optical thickness of the DBR makes it difficult for light to penetrate the DBR layers and reach the DBR-metal interface or cavity and, thereby, reduces the coupling between the incident light and the TP mode, and decreases the peak absorptance. Another approach to enhance the Q-factor of TP resonance is to sandwich a cavity with an optical
Simulated absorptance spectra and electric field distribution (insets) for (a) pure Ge/ZnS DBR-based TP structures, (b) monolayer (ZnS) cavity-enhanced TP structures, and (c) bilayer (Ge/ZnS) cavity-enhanced TP structures for various DBR layers. (d) Simulated Q-factor (left y-axis, black) and peak absorptance (right y-axis, red) of the DBR, DBR + monolayer, and DBR + bilayer structures versus the film thickness (excluding gold film thickness).

Fig. 2.

For a lossless medium cavity, the Q-factor can be enhanced with a longer cavity length corresponding to a larger optical thickness of cavity layer(s). The bilayer structure utilizes high refractive index of Ge to increase the optical thickness of the cavity. Compared to the single ZnS (low index material) layer cavity, the additional Ge layer can increase the optical thickness with a relatively smaller film thickness, and avoid the large thickness of one layer, which alleviates difficulty in film deposition. As shown in Fig. 2(d), if a high peak absorptance (\( A > 0.9 \)) is maintained, the highest achievable Q-factors corresponding to a pure DBR-based TP structure (\( Q \sim 180 \)) and a monolayer cavity-enhanced TP structure (\( Q \sim 307 \)) are lower than that of bilayer cavity-enhanced TP structure (\( Q \sim 453 \)).

According to the designed thickness for a bilayer cavity-enhanced TP structure with tunable emission, gold film and the GST layers are fabricated with magnetron sputtering, and the Ge/ZnS alternating layers are fabricated with E-beam evaporation. The actual thicknesses of the layers are measured with cross-sectional scanning electron microscope (SEM) images [inset of Fig. 3(b)]. The as-deposited GST film is in an amorphous phase (aGST). To obtain cGST, the whole structure was annealed on a heating stage at a temperature of 170 °C for 15 min. The absorptance of the bilayer cavity-enhanced TP structure is calculated with normal reflectance (\( A = 1 - R \)) measured by a Hyperion 1000 infrared microscope equipped with a MCT detector. For both aGST and cGST, the experimental absorptance [Fig. 3(b)] is compared with a simulated absorptance [Fig. 3(a)]. Actual thicknesses of the layers are used for simulation. For aGST, the Q-factor of absorption peak at 4.045 μm is about 156 which is slightly lower than simulated Q-factor 279 of absorption peak at 4.082 μm. For cGST, there are two absorption peaks located at 4.067 and 4.531 μm with a lower absorptance compared to simulated absorption peaks at 4.027 and 4.451 μm.

To further investigate the tunability of emission, aGST structure was annealed at a fixed temperature 170 °C for different times. Normal emittance of samples with different annealing time (2–14 min) are measured at 140 °C with a Fourier transform infrared spectrometer, Bruker Vertex 70 with a DTGS detector [Fig. 3(d)]. For aGST without annealing, the emittance peak at 4.143 μm has a Q-factor of 172, which is higher than other thermal emitters reported [12,18,30–35]. In addition, for annealing times of 2, 6, 8, 10, 12, and 14 mins, the emittance peaks that are closest to aGST’s peak locate at 4.144, 4.167, 4.099, 4.118, 4.123, and 4.128 μm, respectively (2 and 12 mins curves are not shown in the figure for clarity). The corresponding Q-factors of these peaks are 144, 89, 71, 67, 55, and 47, respectively. The simulated absorptance curves for various crystalline fractions are shown in Fig. 3(c). By controlling the crystalline fraction of GST in bilayer cavity-enhanced TP structure, the Q-factors of these emitters are tuned (from 172 to 47) without significantly changing emission peak wavelengths (ranging from 4.099 to 4.167 μm) and emittance (ranging from 0.44 to 0.68). Considering the new emission peak at 4.6 μm [Fig. 3(d)], the emittance for the aGST and cGST structures is 0.87 and 0.05, respectively, rendering an extinction ratio of 12.5 dB. The reamorphization of GST can be achieved by a laser pulse (fs or ns) [36] or electrical pulse [37]. The polarization and angular dependence of a tunable bilayer cavity-enhanced TP structure emitter is shown in Fig. 4. This structure is polarization insensitive (within 40° incident angle range). This polarization insensitivity can be
attributed to the Tamm plasmon polaritons, which can be excited with both TE and TM incident light [17].

In conclusion, we demonstrate a tunable narrowband thermal emitter based on a bilayer cavity-enhanced TP structure and phase-changing material GST. The bilayer cavity-enhanced TP structure increases the $Q$-factor of the resonance, compared to a similar thickness pure DBR structure and a monolayer cavity structure and, therefore, ensures high absorbance/emittance. The high emission $Q$-factor (172) is achieved by this structure with adequate emittance ($\varepsilon \sim 0.7$). Moreover, the emission $Q$-factor is tunable (172 to 47) with a variable crystallization fraction of GST. The combination of a high $Q$-factor TP structure with phase-changing material not only can facilitate the IR gas sensing at different temperatures (with different absorption bandwidth), but also can be employed in other potential applications, e.g., adaptive IR camouflage.

**Funding.** National Key Research and Development Program of China (2017YFA0205700); National Natural Science Foundation of China (NSFC) (61425023, 61575177, 61775194).

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