Ultrafast grating-based spin VCSELs

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***Abstract*—Conventional VCSELs are bandwidth-limited to 30–50 GHz due to carrier dynamics in intensity modulation. Polarization modulation (PM) via birefringence-induced mode splitting enables much higher frequencies, offering a path toward ultrafast optical interconnects. We employ Plane-Wave Admittance Method (PWAM) to design monolithic surface gratings that engineer high phase anisotropy (γ_p) while minimizing loss anisotropy (γ_a). By optimizing grating period, fill factor, depth, and cap layer thickness, we achieve >280 GHz frequency splitting with low dichroism and practical photon lifetimes. Our results present a compact, integrable solution for birefringence control in spin-VCSELs, paving the way for efficient PM-based data transmission.**

***Index Terms*—spin-VCSEL, grating, anisotropy, Polarization Modulation**

I. Introduction

Vertical-Cavity Surface-Emitting Lasers (VCSELs) are compact, energy-efficient light sources used in optical interconnects, 3D sensing, and photonic integration. While conventional VCSELs rely on intensity modulation (IM), their bandwidth is fundamentally limited to $30-50\,\text{GHz}$ by carrier dynamics and photon lifetime [1].

Polarization modulation (PM) via birefringence-induced splitting in spin-VCSELs offers a high-speed alternative. Here, oscillations between orthogonal polarizations are governed by the birefringence-induced frequency splitting $\delta\nu = \gamma_p/\pi$, with values exceeding 200 GHz demonstrated in GaAs-based devices [2], [3]. Key to effective PM is combining large birefringence (high γ_p) with low dichroism (low γ_a), ensuring stable, ultrafast polarization switching.

Early methods to enhance birefringence used strain engineering, mechanical stress, or thermal tuning, but suffered from complexity, hysteresis, or device degradation. Integrated surface gratings emerged as a compact alternative, allowing engineered birefringence with reduced fabrication overhead [3], [4]. However, previous designs often introduced excess loss anisotropy, reducing photon lifetime τ and damping polarization oscillations.

Our work builds on these efforts by optimizing grating geometry and cap layer thickness to achieve over 280 GHz frequency splitting with near-zero γ_a and practical τ, enabling efficient PM beyond the limits of IM.

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II. Grating design for high lifetimes

VCSELs lack inherent polarization preference due to their symmetric cavity and polarization-independent Bragg mirrors. Although weak polarization selection can arise from crystal alignment, the two orthogonal modes remain nearly degenerate, making polarization switching likely under small perturbations.

To suppress this instability, we introduce anisotropy via a monolithic GaAs surface grating [5], integrated into a VCSEL emitting at $\lambda = 980\,\text{nm}$. The grating, infinite along the y-axis, is defined by pitch L, fill factor f, and lamella thickness d_{grat}. It breaks in-plane symmetry, splitting resonance conditions for TE and TM modes ($\lambda_x \neq \lambda_y$), as discussed in the following Section.

Grating performance depends strongly on L, which governs three regimes: diffraction, high reflectivity, and effective permittivity (Fig.1). Scaling L shifts these regions spectrally, enabling design around the VCSEL emission. Fig.1a–1c show reflectivity evolution with $L = 0.28$, 0.56, and $0.84\,\mu\text{m}$ (scaling by factors of 1–3). We select $L = 0.84\,\mu\text{m}$ to center the emission in the high-reflectivity regime, which also aligns with typical lithography limits.

The fill factor f is then optimized at this fixed L. In this case, $f = 0.6$ yields high reflectivity $\geq 70\%$ for both polarizations across a broad thickness range. This ensures similar photon lifetimes and reduced polarization-dependent loss. Modal properties found using the Fourier modal method [6] are examined.

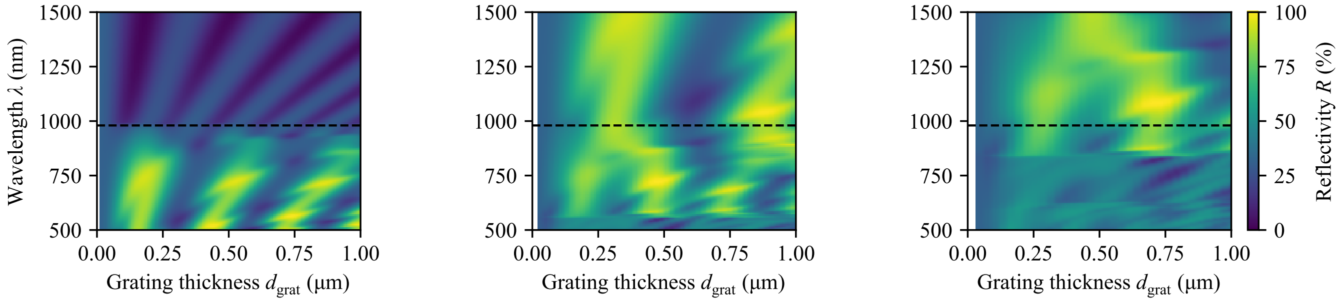
III. Grating design for ultrafast modulation

To enable polarization switching, a large frequency separation between TE and TM modes—termed phase anisotropy γ_p—is essential. It is defined as:

$$\gamma_p \approx \pi c \left| \frac{1}{\Re(\lambda_{\text{TE}})} - \frac{1}{\Re(\lambda_{\text{TM}})} \right| \tag{1}$$

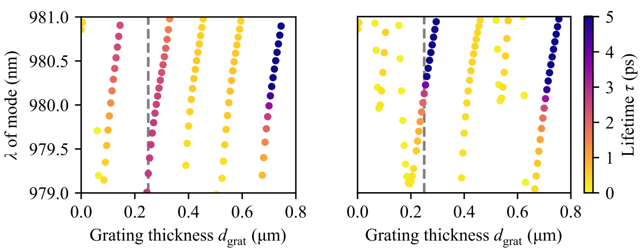
yielding the oscillation frequency $\delta\nu = \gamma_p/\pi$. Conversely, loss anisotropy γ_a arises from differences in modal losses:

$$\gamma_a = \frac{|\Im(\omega_{\text{TE}}) - \Im(\omega_{\text{TM}})|}{2} \tag{2}$$



(a) $L = 0.28\,\mu m$, $f = 0.77$ (b) $L = 0.56\,\mu m$, $f = 0.77$ (c) $L = 0.84\,\mu m$, $f = 0.77$

Fig. 1: Calculated TE reflectivity on GaAs grating. The band edge shifts as period increases from $L = 0.28\,\mu m$ to $0.56\,\mu m$ and $0.84\,\mu m$, scaling by factors of 2 and 3, respectively. This vertical shift of boundaries is independent on f and is identical for TM polarization.



(a) TM modes (b) TE modes

Fig. 2: Resonant wavelengths with photon lifetimes for TE and TM modes of a VCSEL with $d_{cap} = 100\,nm$, $L = 0.84\,\mu m$, and $f = 0.4$. The gray dashed line highlights $d_{grat} = 0.25\,\mu m$.

γ_a is undesired — it causes the polarization to stabilise at the mode (symmetry) with the higher lifetime, thus removing the polarization oscillation behaviour. Moreover, loss anisotropy reduces $\delta\nu$ via $\delta\nu = (\gamma_p - \alpha\gamma_a)/\pi$, where α is line-width enhancement factor, so it must be minimized.

We scanned grating thicknesses from $0 - 1\,\mu m$, optimizing γ_p and γ_a by calculating them from the complex frequencies of the found modes. A first optimal point was found at $d_{grat} = 0.58\,\mu m$ with $\gamma_p = 159\,GHz$ and acceptable photon lifetimes. A second viable solution at $d_{grat} = 0.30\,\mu m$ showed lower lifetimes but significantly reduced γ_a.

To enhance birefringence, the number of top DBR pairs was reduced from 15 to 10, increasing γ_p to $594\,GHz$ but also γ_a to $32.5\,ns^{-1}$. To mitigate this, we modified the cap layer thickness d_{cap} and re-optimized the grating to $d_{grat} = 0.23\,\mu m$. This shifted the modal spectrum while enabling lower losses at $d_{cap} = 105\,nm$, reaching $\gamma_p = 711\,GHz$ and $\gamma_a = 8.7\,ns^{-1}$. However, the photon lifetimes dropped below $1\,ps$.

To recover τ_{ph}, we refined the fill factor to $f = 0.4$, improving both τ_{TM} and τ_{TE} to $\approx 2.7\,ps$ while maintaining high γ_p. A final d_{cap} adjustment to $100\,nm$ yielded matched lifetimes and minimized dichroism to $\gamma_a = 0.01\,ns^{-1}$ at $\gamma_p = 889\,GHz$, resulting in a splitting of $283\,GHz$.

IV. Conclusion

We have simulated VCSELs with surface gratings using the Fourier modal method, addressing the need for compact devices with fabrication-ready birefringence control for ultra-fast polarization dynamics [4]. Our results show that tailoring grating parameters enables high phase anisotropy γ_p while minimizing loss anisotropy γ_a—a key challenge in birefringent VCSELs—without compromising photon lifetime τ. The grating period L is tuned to align the reflectivity peak with the emission wavelength, the fill factor f ensures >85% reflectivity for both TE and TM modes, and d_{grat} is optimized for birefringence. Loss balancing is achieved by adjusting the cap layer thickness d_{cap}. This method also offers a path to compensate for interface anisotropy in realistic devices.

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