Real-time dynamic wavelength tuning and intensity modulation of metal-clad nanolasers

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Abstract: To realize ubiquitously used photonic integrated circuits, on-chip nanoscale sources are essential components. Subwavelength nanolasers, especially those based on a metal-clad design, already possess many desirable attributes for an on-chip source such as low thresholds, room-temperature operation and ultra-small footprints accompanied by electromagnetic isolation at pitch sizes down to ~50 nm. Another valuable characteristic for a source would be control over its emission wavelength and intensity in real-time. Most efforts on tuning/modulation thus far report static changes based on irreversible techniques not suited for high-speed operation. In this study, we demonstrate in-situ dynamical tuning of the emission wavelength of a metallo-dielectric nanolaser at room temperature by applying an external DC electric field. Using an AC electric field, we show that it is also possible to modulate the output intensity of the nanolaser at high speeds. The nanolaser’s emission wavelength in the telecom band can be altered by as much as 8.35 nm with a tuning sensitivity of ~1.01 nm/V. Additionally, the output intensity can be attenuated by up to 89%, a contrast sufficient for digital data communication purposes. Finally, we achieve an intensity modulation speed up to 400 MHz, limited only by the photodetector bandwidth used in this study, which underlines the capability of high-speed operation via this method. This is the first demonstration of a telecom band nanolaser source with dynamic spectral tuning and intensity modulation based on an external E-field to the best of our knowledge.

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1. Introduction

With increased efforts to integrate photonic components on-chip comes a need for nanoscale light sources with ultra-compact footprints and low power consumption among other desirable attributes. To this end, various types of nanolasers have been demonstrated over the better part of the past two decades such as those based on photonic crystals [1–3], nanowires [4–7], metallo-dielectric cavities [8–12] and plasmonic cavities or spasers [13–15] to list a few. Along with their nanoscale dimensions and in the case of metal-clad cavities, even subwavelength footprints, most such nanolasers have been shown to demonstrate qualities ideal for an on-chip source such as low thresholds [14,16], dense-integration capability [17,18] and electrical injection with room-temperature operation [19]. Another characteristic that can prove to be of great value for these sources is the ability to shift their wavelength of emission as well as to modulate their output intensity at high speeds. Control over the emission wavelength and intensity would be especially well-suited for dense wavelength division multiplexing (WDM) applications at a chip-scale level [20]. Additional applications include lidar systems, virtual/augmented reality devices and imaging/sensing.
Widespread efforts to control the emission wavelength of nanocavity lasers have been reported thus far based on differing physics [21]. Examples of wavelength tuning mechanisms include varying the material composition of the active medium to alter the bandgap [4,5,22,23], physically transforming the size or shape of the cavity [24–26], altering the refractive index of the environment [27], applying pressure [6,28] as well as inducing a temperature-dependent Varshni shift of the bandgap [29]. Despite the plethora of methods, the above-mentioned approaches exhibit certain shortcomings. For instance, in devices where the material composition is varied or the cavity geometry is modified, the alterations made are static and irreversible whereas ideally, the tuning should be dynamic (in other words, achieved in a reversible manner) and in real-time. Although mechanisms based on index, pressure and temperature are reversible, the bandwidths achieved via these methods reach a few MHz at best, while on-chip communications require much higher speeds. Similarly, despite studies demonstrating high-speed intensity modulation of nanolasers [1,2,30,31], most of the methods involve direct modulation of the pump and then the response of the nanolaser is shown to merely follow the pump modulation. In these cases, introducing independence between the pump and the modulation scheme would allow for an extra degree of freedom in controlling the emission intensity.

In this work, we report on simultaneously tuning the emission wavelength as well as altering the output light intensity from a metallo-dielectric nanolaser. The mechanism is based on applying an external electric field to the nanolaser device which induces modifications in both the overlap of the electron and hole wavefunctions as well as the bound state energies via the quantum-confined Stark effect (QCSE). Since the alterations to the bandgap are due to electronic effects, it is possible to attain much higher speeds than bandgap modifications based on pressure or temperature [32]. We show that tuning based on external field is both reversible in nature and offers a fine range of tuning. Using this scheme, we demonstrate intensity modulation of up to 400 MHz, limited only by the detector bandwidth, as a proof of concept for our nanolaser’s high-speed capability. Additionally, we complement the dynamic fine-tuning results with geometry-based coarse-tuning ones by altering the cavity design. This is the first report on real-time tuning and high-speed modulation of metal-clad nanolasers based on external field, to the best of our knowledge. This study lays the path for future work on attaining room-temperature, high-speed, tunable nanolasers under electrical injection for possible applications in on-chip data communications, lidar, virtual/augmented reality devices and imaging/sensing.

This paper is organized into five sections. In Section 2, some insight into the design and fabrication of the multiple quantum well (MQW) nanocavity is provided along with spectral characterization confirming lasing at room temperature. Additionally, geometry-based coarse tuning is demonstrated by altering the cavity size of the nanolasers. In Section 3, we present our experimental results on the continuous fine-tuning of the lasing wavelength as well as high-speed modulation based on an external field. The experimental and theoretical results are compared and discussed in Section 4 and finally, Section 5 concludes the manuscript.

2. Device design and geometry-based coarse wavelength tuning

The design and fabrication of the metallo-dielectric nanocavity used in this study is built upon the device first reported by Nezhad et al., [9] with certain modifications to enable external E-field application. First, the gain comprises of 300 nm of InGaAsP multiple quantum wells (MQWs) with wells and barriers of 10 and 20 nm thickness, respectively. Secondly, Al₂O₃ serves as the dielectric shield instead of the more commonly used SiO₂ owing to better thermal conductivity of the former [10]. In order to apply an electric field to tune/modulate the emission from the cavity, two additional fabrication steps were added as illustrated in the device schematic in Fig. 1(a). A layer of SiO₂ (~500 nm) was deposited to function as the insulator and then a thin film of ITO (~20 nm) was deposited on top of this dielectric layer to serve as the bottom electrode. Although ITO is transparent at the NIR wavelengths of the nanolaser emission, it is still optically lossy and
therefore, the film was chosen to be as thin as possible. Figure 1(b) is a cross-sectional FIB image post-completion of all fabrication steps depicting a representative device with a gain radius of 455 nm.

Fig. 1. (a) Device schematic of the metallo-dielectric nanolaser with constituent materials labelled. The gain comprises 10 nm thick InGaAsP quantum wells (shown in red) and 20 nm thick barriers (shown in black). The device is pumped from the bottom (red arrow) and emits in the same direction (shown via the red beam). The ITO thin film and Ag cladding serve as the bottom and top electrodes respectively, across which voltage is applied to the device (b) FIB cross-section image of a representative device with false color and constituent materials labelled.

The photoluminescence (PL) of the nanocavities was then characterized at room temperature with a micro-photoluminescence (µ-PL) setup akin to the one used in Pan et al., [11]. A Nd:YAG laser operating at 1064 nm was used to optically pump the devices. The spectral features for a device of gain radius 465 nm are illustrated in Figs. 2(a) and 2(b), clearly establishing the coherent nature of emission from the nanocavity. Firstly, the spectral evolution in Fig. 2(a) shows the emergence of a narrow peak at 1478 nm that dominates all other peaks as the peak pump intensity is increased. Secondly, and providing stronger evidence for lasing, the linear light-out vs. light-in (LL) curve portrayed in Fig. 2(b) exhibits a clear kink which signifies the lasing onset; the log-log plot of the same data in the inset depicts the S-shaped curve that is conventionally associated with lasing in nanolasers [11,33–35]. Eigenmode simulations of the cavity suggest that the lasing mode is a whispering gallery mode (M=3) as depicted in the inset of Fig. 2(a).

In Fig. 2(b), the peak emission wavelength - \( \lambda_{\text{peak}} \) is also plotted alongside the LL curve. As clearly observed, significant alterations in the peak wavelength (specifically, blue-shifts) can be induced via increasing pump powers. Although the electric field-based method presented in this study in no way supersedes the tuning possible with varying pump powers, the former can be more advantageous in certain scenarios. Firstly, an external field method is applicable regardless of whether the device is above or below threshold. In contrast, the blue-shift incurred via increasing the pump is mainly viable for devices operating below threshold. Secondly, and most importantly, the electric field method provides an independent manner to control the emission without having to alter the pump properties. This becomes especially relevant if a single pump is pumping several nanolasers and the goal is to tune the emission of only one of the emitters. In this scenario, by applying an electric field exclusively to the device of interest while maintaining a constant pump rate, the other emitters are left unperturbed by the tuning process.

A nanolaser’s emission wavelength can also be tuned according to the size of the cavity as it modifies the cavity modes supported within the gain-bandwidth window (~1.3-1.6 \( \mu m \) for InGaAsP MQWs). Since cavity modes can vary greatly in their resonant wavelengths, Q’s and energy confinement factors, by designing and fabricating nanocavities with varying radii, the emission wavelength of our nanolasers can be coarsely but widely tuned in a static manner as illustrated in Fig. 2(c). More interestingly, due to the ultrasmall cavity volume, it is possible to tune the lasing wavelength by substantial amounts with relatively small alterations in the
Fig. 2. (a) Spectral evolution showing emergence of a narrow peak at 1478 nm with increased peak pump intensity. The lowest two spectral curves (red and yellow) are multiplied by a constant for easier distinguishability. Inset: Simulated modal profile of whispering gallery mode (M=3) postulated to be the lasing mode. (b) Linear LL curve (blue) illustrating onset of lasing and peak wavelength of emission (green). Inset: The same data plotted on a log-log scale showing S-shaped curve and kink. (c) Normalized spectra showing geometry-based tuning of the emission wavelength by varying the radius of the nanocavity pillar during the design stage.

gain radius. For instance, as the radius of the gain is varied from 365 to 380 nm, the emission wavelength can be tuned from 1401 to 1461 nm – a range of 60 nm. Spectra from another sample are also shown on the far right of Fig. 2(c) for radii of 400 and 405 nm. Although the fabrication procedures used for the two samples shown in Fig. 2(c) differed slightly, their spectra are plotted together to demonstrate the possibility of extending the lasing wavelength range to cover telecom bands from the E all the way up to the C band. It is important to emphasize here that the lasing mode is determined not just by the values of its Q and energy confinement factor, but also its proximity to the peak of the modal gain spectrum. Thus, similar to other studies where either the material composition is varied [4,5,22,23] or the cavity is physically altered [24–26], varying the radii of metal-clad nanolasers in the design phase itself provides a static or irreversible method of tuning the wavelength.
Fig. 3. (a) Real-time dynamic tuning of lasing wavelength by applying DC electric field/voltage across the device while pumping optically. Inset: Different set of spectra from the same device confirming reversible nature of the external E-field technique (b) Peak output intensity percentage (blue circles) and tuning range in peak wavelength - $\Delta \lambda$ (red diamonds) – plotted as a function of the voltage applied to the device. The intensity can be attenuated by up to $\sim 89\%$ and the wavelength can be red shifted by $\sim 8.35\text{ nm}$ at maximum when $\sim 8.8\text{ V}$ is applied across the device. (c) The intensity attenuation and wavelength detuning from (b) plotted together. The detuning point at which the intensity falls to 50% was determined to be at $\sim 3.7\text{ nm}$ via a linear fit.

3. Dynamical experimental results

3.1. Dynamic and real-time fine wavelength tuning

In order to tune the nanolaser wavelength in real-time, an external electric field was applied perpendicular to the MQWs as depicted in Fig. 1(a). A Cu substrate connected to the Ag-metal cladding was chosen as one electrode while the ITO thin-film functioned as the other. Although not depicted in the device schematic in Fig. 1(a), this Cu electrode is the substrate to which the nanolasers, which are covered with Ag cladding, are bonded using a conductive silver epoxy; additional details about the bonding process can be found in [11,16]. A voltage source (Keithley 2400) was then used to apply the voltage across the device while it was optically pumped at an input optical intensity of $\sim 2*P_{th}$, where $P_{th}$ denotes the pump intensity at the device’s lasing threshold. The nanolaser’s emission spectra were subsequently recorded with a monochromator. Figure 3(a) illustrates the effect of applying varying amounts of DC voltage on the lasing spectra of the nanolaser device for which the PL characterization is shown in Figs. 2(a) and 2(b). To
provide better intuition, values of the electric field are reported as voltage instead. From Fig. 3(a), it can be clearly observed that with increasing voltage, the nanolaser spectra are affected in two ways. First, the output intensity of the emitted light decreases monotonically until the emission is almost completely suppressed at the highest applied voltage of 8.8 V. Secondly, the emission wavelength redshifts, also monotonically, with increasing voltage. It is important to note that both modifications to the spectra are reversible in nature, as depicted in the inset of Fig. 3(a). This means that, although applying voltage to an unbiased nanolaser (shown as blue, solid line) attenuates and red-shifts its spectrum (red, dashed line), the spectrum would revert back to the original behavior if it were to be measured again without any external field (orange, solid line with round markers). This reversible nature of the alterations is not shown in the main portion of Fig. 3(a) as the device was pushed beyond the reversible voltage limit (in this case, 8.8 V) and as a result, the ITO thin-film degraded.

To better quantify these effects induced by the external E-field, the nanolaser’s peak output intensity, \( P \), for each applied voltage is plotted in Fig. 3(b) as a percentage of \( P_0 \), the peak intensity in the absence of the E-field/voltage. A monotonic drop in the peak output intensity can be observed with the attenuation as high as \( \sim 89\% \) at the highest E-field/voltage value. Similarly, the alteration of the peak wavelength, \( \Delta \lambda \), plotted on the right axis of Fig. 3(b) is also significant and exhibits a redshift of around 8.35 nm at maximum voltage. It is important to emphasize here that with the application of an external E-field/voltage, much finer tuning is afforded compared to the case of geometry-based tuning (Fig. 2(c)). A tuning sensitivity, defined as \( \Delta \lambda / \Delta V \), of \( \sim 1.01 \) nm/V is found via a linear fit to the wavelength data shown in Fig. 3(b). This corresponds to a change of close to half the laser linewidth per volt, where the linewidth is the one considered in the absence of electric field (\( \sim 2.16 \) nm). Additionally, a peak wavelength-tuning step of smaller than 150 pm can be achieved with only a slight increment in the applied voltage (\( \sim 0.65 \) V). This fine control also extends to the output intensity, which can be attenuated by lower than \( \sim 2\% \) as the voltage is varied. Such precise tuning of the lasing peak wavelength coupled with the real-time, reversible nature of the alterations can prove to be invaluable for applications such as on-chip optical communications with WDM [36]. In addition, since the intensity attenuation and wavelength detuning are synchronous events, a direct correlation between the two is illustrated in Fig. 3(c). It can be observed from this plot that the detuning point at which the peak intensity falls to 50\% of its zero-field value (in other words, when it decreases by 3 dB) is at \( \sim 3.7 \) nm, determined via a linear fit to the data.

### 3.2. Intensity modulation

For practical applications, high-speed modulation of nanolasers is desirable and in some cases such as for communication purposes, even imperative. To demonstrate the high-speed modulation capability of our devices under an external E-field, a small-signal modulation experiment was carried out where the nanolaser was pumped optically while an AC electric field was applied across the device’s contacts via a function generator (Keysight N9181A). This input sine wave voltage was purely an AC signal with no DC components and was measured via an electrical spectrum analyzer (ESA, Keysight N9181A). The \( V_{\text{RMS}} \) of the input sine wave was confirmed to be \( \sim 1.35 \) V (corresponding to a peak voltage of \( V_{\text{peak}} \sim 1.9 \) V) with a frequency of \( \sim 400 \) MHz. A peak registered on the ESA at the exact frequency and amplitude of the input waveform is depicted in Fig. 4(a). Emission from the nanolaser was collected using a low-noise, high-gain APD (Thorlabs APD430C) which was then connected to the same ESA. If the device emission follows the AC signal of the voltage source, a peak would be registered in the ESA at the exact frequency of the AC input signal shown in Fig. 4(a). Figure 4(b) illustrates the result of applying the 400 MHz sinusoidal AC voltage signal to the nanolaser which registers a clear AC signal amplitude on the ESA at \( \sim 400 \) MHz. This result confirms that our nanolaser can be modulated by an AC signal of up to 400 MHz via the external E-field technique.
Fig. 4. (a) 400 MHz AC sinusoidal waveform sourced from a high-speed function generator and measured via an ESA. The $V_{\text{RMS}}$ of the signal is $\sim 1.35 \text{ V}$ (corresponding to a peak voltage of $V_{\text{peak}} \sim 1.91 \text{ V}$). (b) The nanolaser output emission when subjected to the input signal shown in (a) measured via a photodetector connected to an ESA. The amplitude measured is four orders of magnitude lower than the input AC signal. The span of both windows is 2 kHz.

Theoretically, emission alterations of nanolasers based on electronic effects can reach high speeds up to the THz regime [32]. In practice, for example in our study, further demonstrations at higher modulation speeds were impeded by the response of the APD which had a 3-dB bandwidth of 400 MHz. Additionally, the measurement error increases as the frequency is increased due to the ohmic contacts deposited on the nanolaser which are not ideal for high-speed measurements. Consequently, only the response at the highest measurable frequency of 400 MHz is demonstrated as a proof-of-concept for high-speed modulation via the electric-field technique. Modulation at a speed of 400 MHz also confirms that the modulation mechanism is due to electronic instead of thermal effects since the latter would have limited the modulation speed to only a few MHz at most [37]. Future efforts to attain high speeds in the GHz regime and beyond would not only involve employing a detector with much higher bandwidths but would also require altering the electrode design in order to minimize measurement error and realize planarized contacts more appropriate for handling high-speed signals. Such planarized contacts can help significantly reduce the electrical losses between the source and the nanolaser, which are largely responsible for the orders of magnitude difference between the input signal and device output response seen in Figs. 4(a) and 4(b) respectively. Performing the experiment at cryogenic temperatures is another manner in which the nanolaser output levels can be increased as the high optical losses incurred by the metallic cladding are lower at these temperatures.

4. Discussion

We believe that the mechanism behind both the red-shift in emission wavelength and attenuation in intensity is the QCSE, the quantum equivalent of the Franz-Keldysh effect [32]. According to this effect, two separate bandgap modifications occur when a field is applied to a quantum well. First, the electron and hole wavefunctions move in opposite directions relative to each other. This, in turn, reduces the radiative recombination probability and hence, the optical power being emitted. The second consequence of QCSE is the lowering of the bound state energies themselves, which effectively reduces the transition energy (or bandgap) and hence, results in a shift to lower frequencies (i.e., longer wavelengths).

To theoretically probe whether the experimental observations are indeed based on QCSE, semiconductor device analyzing tool SILVACO is used to simulate the effect of an external electric field on a representative nanolaser structure. In the 2-D simulations that are performed, the only pair of bound states that exist for both electrons and holes in this material structure is considered [38]. Additionally, the effect of light holes is not accounted for in the analysis for
the sake of simplicity. The carrier mobility is modeled using a parallel electric-field dependent model while for recombination, spontaneous, Auger and band-band transitions are all considered. The bound states and wavefunctions for each of the nine quantum wells comprising the InGaAsP gain medium are then solved for using the Schrodinger equation as varying voltages are applied to the device. Upon visualizing the results, it is observed that both the bound state energies and the wavefunctions shift during the application of an electric field in the form of voltage. In order to concretely quantify the changes induced, both the bandgap derived from the bound state energies and the wavefunction overlap are used to calculate the material gain spectrum for each of the InGaAsP quantum wells following the procedure outlined in [38]. Finally, the optical mode overlap with the wells is accounted for when calculating the modal gain spectrum for the entire MQW structure for each voltage value [39]. Figure 4(a) depicts the effect on the modal gain curves for a few of the representative voltage values applied to the 2-D nanolaser structure. It can be clearly observed that as the applied voltage increases, the peak of the gain spectra reduces in magnitude and red-shifts in wavelength.

In order to compare the simulated trends with the experimental ones, the change in the peak modal gain wavelength (Δλ) and the percentage alteration in peak modal gain amplitude are plotted with the experimental results in Figs. 5(b) and 5(c), respectively. For both the simulated quantities, the case without an E-field (zero voltage) serves as the initial reference point. The comparison reveals that while the output intensity for both experiment and simulation matched closely (Fig. 5(b)), the amount of tuning in the peak wavelength was higher in simulation than in experiment (Fig. 5(c)). This slight mismatch is expected due to several reasons, the first of which is that the two quantities that are compared – modal gain and emission intensity – are related but not identical to one another. Furthermore, leakage current through the material was observed during experiments. This current arose from fabrication imperfections during the deposition of the ITO thin films used and was not accounted for in the numerical simulations, thus making it another likely reason behind the slight deviation between experiment and simulation. It is also possible that not taking light holes into account for the simulation led to an overestimation of the wavelength tuning. Finally, another cause could lie in the fact that simulations were performed in 2-D and therefore, may not be able to fully reproduce the experimental scenario. Despite the differences, the similarities between experiment and simulation build confidence that QCSE is the underlying mechanism behind the observed device behaviors.

Another interesting observation worth mentioning is the evolution of the linewidth of the emission peak that is shown in Fig. 3(a). It was found that the linewidth exhibits an initial narrowing as the voltage increases (till about 3.9 V), followed by a period of near constancy (4.5 V to 5.2 V), a subsequent sudden and drastic narrowing at 5.8 V and finally, broadening starting at 6.5 V. Some past studies suggest that both linewidth narrowing as well as broadening have been observed based on the QCSE. Whereas the former can be demonstrated in cases where exciton states couple less efficiently to defect-charge fluctuations [40], the latter can be a result of field-induced carrier tunneling [41]. It is possible that a combination of such mechanisms is responsible for the linewidth behavior of our device. Although a detailed exploration of this phenomenon lies beyond the scope of this study, it is an important effect worth analyzing in a future work.

Therefore, despite the presence of a small amount of leakage current, given the high-speed modulation result of Fig. 4(b), the emission alterations reported in this study are not believed to be caused by thermal tuning. Though applying heat to the gain material can have a similar effect of both attenuating the intensity and red-shifting the emission wavelength, heat-based modifications to the bandgap cannot occur at speeds exceeding a few MHz [37].
Fig. 5. (a) Numerically calculated modal gain spectra of InGaAsP MQW gain medium comprising of nine quantum wells. The bound state energies and carrier wavefunctions are solved using 2-D SILVACO simulations. The simulations and experiments are compared in (b) where peak modal gain (green circles) is compared to experimental emission peak intensity (red triangles) and (c) where the shift in the peak modal gain (green circles) is compared to that in the experimental peak lasing wavelength (red diamonds), $\Delta \lambda$. The trend of the experimental results matches that of the simulations but the two are not identical and not expected to be (especially for the wavelength) since any proportionality constants for the gain-intensity relationship are not considered here. Moreover, the presence of a small amount of leakage current in the experiment is also not accounted for in the 2-D simulation.
5. Conclusion

The real-time wavelength tuning and intensity modulation of metal-clad nanolasers using an external electric field are presented in this study. While most demonstrations of tuning for nanoscale sources in the literature are based on geometry-based, irreversible tuning, having real-time dynamic control is much more advantageous for on-chip and other applications. In this work, we demonstrated real-time, reversible spectral tuning and high-speed intensity modulation of a metallo-dielectric nanolaser. The emission wavelength can be tuned by up to 8.35 nm with a tuning sensitivity, defined as $\Delta \lambda / \Delta V$, of $\sim 1.01$ nm/V. Additionally, the emission intensity can be attenuated by as much as $\sim 89\%$ and this alteration can be modulated up to 400 MHz, only limited by the detector’s bandwidth used in this study. Simulations suggest that QCSE accounts for the underlying bandgap modifications, inducing a shift in the carrier wavefunctions as well as lowering the bound state energies. Although some newer studies published during the preparation of this manuscript have reported similar electric field-based changes in nanoribbon lasers [7], the nanolasers shown in this study are the first telecom band demonstration of dynamical tuning/modulation based on an external electric field. Future work on demonstrating modulation in the GHz regime and with continuous-wave electrically pumped devices operating at room temperature will bring us a step closer to realizing potential nanolaser applications in various areas such as photonic integrated circuits, virtual/augmented reality devices, lidar systems and imaging/sensing devices.

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