Integrated electro-optic isolator on thin-film lithium niobate

Optical isolators are indispensable components of almost any optical system and are used to protect a laser from unwanted reflections for phase-stable coherent operation. The emergence of chip-scale optical systems, powered by semiconductor lasers that are integrated on the same chip, has generated a demand for a fully integrated optical isolator. Conventional approaches, which rely on the use of magneto-optic materials to break Lorentz reciprocity, present substantial challenges in terms of material integration. Although alternative magnetic-free approaches have been explored, an integrated isolator with a low insertion loss, high isolation ratio, broad bandwidth and low power consumption on a monolithic material platform is yet to be achieved. Here we realize a non-reciprocal travelling-wave-based electro-optic isolator on thin-film lithium niobate. The isolator enables a maximum optical isolation of 48.0 dB with an on-chip insertion loss of 0.5 dB and uses a single-frequency microwave drive power of 21 dBm. The isolation ratio remains larger than 37 dB across a tunable optical wavelength range from 1,510 to 1,630 nm. We realize a hybrid distributed feedback laser–lithium niobate isolator module that successfully protects the single-mode operation and linewidth of the laser from reflection. Our result represents an important step towards a practical high-performance optical isolator on chip.

Recent decades have witnessed the rapid advancement of integrated photonic technology for applications including optical communications, microwave photonics, computing, optical atomic clock, quantum information processing, light detection and ranging and sensing. In parallel, hertz-linewidth semiconductor lasers have been recently demonstrated on chip, showing promise as photonic engines for future large-scale photonic processors. The urgent need to combine the narrow-linewidth semiconductor laser with functional photonic modules demands a high-performance, reliable integrated optical isolator.

Various approaches for realizing integrated optical isolators have been demonstrated, including magneto-optics, electro-optics (EO), acousto-optics and optical nonlinearities. Magneto-optical isolators feature robust operation and broad bandwidth, but face challenges of material integration or interfacing with atomic systems that require optical readout and are highly sensitive to magnetic interference. Nonlinear optical approaches either require additional optical pump lasers and filters or show power-dependent isolation. Recent demonstrations based on EO and acousto-optics...
The total phase accumulation $\phi$ sinusoidal microwave field, at frequency $f_R$, the accumulated optical phase of the laser output after passing a phase modulator of length $L$ is equal to zero when $f_s = mc/(2L\alpha_{opt})$, where $m$ is an integer number and $c$ and $\alpha_{opt}$ are the light velocity and optical group index, respectively. Any reflected laser light that propagates in the backward direction undergoes efficient phase modulation, which results in $V_{opt}/V_{BW} \gg 1$. Forward; BB.

Thin-film (TF) lithium niobate (LN) is well positioned to address this challenge, as it simultaneously supports phase-only modulation and low propagation loss. Recent advancement of the integrated LN platform has enabled ultralow-loss travelling wave EO modulators operating at complementary-metal–oxide–semiconductor-compatible voltages and high EO bandwidth. Other excellent photonic properties, including wide transparency window, large second-order and Kerr nonlinearity and large piezoelectric coefficient, make LN a highly compelling choice for realizing future coherent optical systems.

In this paper, we demonstrate an integrated isolator based on a travelling-wave EO modulator realized in TF LN, and use it to protect a distributed feedback (DFB) laser which is edge coupled to the TF LN chip (Fig. 1). The phase modulator is driven with a single-tone sinusoidal microwave field, at frequency $f_s$, propagating in the direction opposite to the optical signal. The total phase accumulation $\phi(f_{RF}, t)$ is equal to $\frac{V_{RF}}{V_{opt}} \int_0^L e^{-\alpha_{opt} z} \cos[2\pi f_{RF}(z_{opt} + c n_{opt} - t)] dz$, where $V_{RF}$, $V_{opt}$, $f_{RF}$, $\alpha_{opt}$, $n_{opt}$ and $c$ are the peak voltage, half-wave voltage, microwave power attenuation constant, optical group index, microwave phase index and light velocity in a vacuum, respectively. Labels + and − are chosen to indicate situations when the optical and microwave fields are counter-propagating and co-propagating, respectively. Since the laser output is counter-propagating with the microwave signal, the phase accumulation is a periodic function of the propagating distance in the modulator. Assuming $a = 0$, the phase accumulation equals zero when the microwave driving frequency is $f_{RF} = mc/(2L\alpha_{opt})$, where $m$ is an integer number. In this case, the laser light is not modulated and is fully transmitted in the forward direction. On the other hand, reflected light travelling in the backward direction co-propagates with the microwave field, resulting in a linearly increasing phase accumulation for any given $t$. The reflected light at the input frequency $f_0$ can be fully depleted when the modulation depth is approximately equal to $0.765\pi$, satisfying $f_0/beta = 0$, where $f_0$ is the zeroth-order Bessel function of the first kind (Supplementary Fig. 1). In this case, all the optical power is distributed to frequencies equal to $f_0 \pm nf_{RF}$, where $n$ is an integer (Fig. 1b).

Figure 1c shows an optical micrograph of the LN chip with modulator lengths ranging from 1.25 cm to 2.00 cm with a step size of 0.25 cm. The chip is fabricated on a 600 nm X-cut LN wafer with an etch depth of 320 nm (Methods). The group velocity of the light matches the phase velocity of the microwave ($n_{opt} = n_{RF} = 2.26$) to ensure the efficient phase modulation at microwave driving frequencies of tens of gigahertz. The chip has both input and output mode converters for a low-loss interface with the DFB laser (insertion loss, 2 dB per facet) and lensed fibre (insertion loss, 3 dB per facet). Our device utilizes a simple optical structure of a single modulated waveguide and operates with a single-frequency microwave drive on the condition that the microwave power is tuned to the pump depletion point.

We show that the integrated phase modulator allows for high-performance optical isolation at the laser frequency. First, we characterize the isolation ratio and optical bandwidth using a tunable continuous-wave laser (Methods) and a phase modulator of 1.75 cm in length. The isolation ratio is defined as the ratio of optical power propagating in the forward and backward directions at laser frequency.
Figure 2a plots the optical spectrum in both forward and backward directions using $f_{RF} = 26.5$ GHz ($m = 7$). In the forward direction, the laser light (wavelength, 1,553.2 nm) is nearly completely transmitted, with an on-chip insertion loss of 0.5 dB. In the backward direction, however, most of the light is coupled to sidebands, at a frequency spacing equal to harmonics of $f_{RF}$ (26.5 GHz). Next, we demonstrate the ability of our isolator to operate at different microwave frequencies, namely, $f_{RF}$ values of 26.5 and 10.4 GHz (Fig. 2b,c). At 26.5 GHz, an isolation ratio of 48 dB is achieved at the pump wavelength, using a microwave power of 21 dBm, corresponding to $\beta = 0.765 \pi$ with $V_{\pi} = 4.7$ V. Also, a microwave power stability of 1% is required for achieving >44 dB isolation ratio (Methods). Since the microwave power scales with $V_{\pi}^3$, power reductions are possible by reducing $V_{\pi}$. At 10.4 GHz, the isolation ratio is estimated to be >44 dB (measurement limited by the instrumental resolution). At both frequencies, the isolation is probably limited by the purity of the optical polarization (Methods). The ability to achieve large isolation using different microwave frequencies offers flexibility in the system design: for example, it allows sidebands to be placed off-resonance with the laser cavity, or outside the laser instability range, thus ensuring stable laser operation. We note that the forward light exhibits first sidebands that are 37 dB lower than the pump intensity, which is attributed to the microwave power attenuation along the electrode ($\alpha = 0.7$ dB cm$^{-1}$ GHz$^{-0.5}$) and the facet reflection. These sidebands cause minimal loss and intensity modulation (Supplementary Fig. 2) to the laser signal and could be filtered out. We further tested the optical bandwidth of our device by tuning the laser wavelength and repeating the isolation ratio measurement from 1,510 to 1,630 nm. As shown in Fig. 2d, the optical isolation remains >37 dB across the entire tuning range. We note that this bandwidth is tested using a single-frequency laser and should not apply for a broadband light source input. In principle, the EO isolator could also be used with directly modulated laser or laser followed by an EO modulator as long as the modulation frequency is smaller than the microwave frequency $f_{RF}$ used to drive the isolator, to avoid spectral overlap between the input and backward sidebands$^{35}$. Finally, we tested the stability of the isolation ratio at 1,555 nm and achieved an isolation ratio of 41.30 ± 0.56 dB over 12 hours (Methods).

In cases where the total power reflected to the laser needs to be minimized, an add–drop ring-resonator filter, transmitting at the laser wavelength and featuring a free spectral range (FSR) larger than $f_{RF}$.
Isolation = 48 dB

Finally, we verify the performance of our optical isolator using a complete III–V LN laser module (Fig. 1a). We construct the system by edge coupling a prefabricated InP DFB laser with the LN isolator chip (Fig. 4a). The coupling between the III–V and LN components is carefully engineered via mode matching, which leads to a measured 2 dB loss at the interface (Methods). To assess the effectiveness of the isolator in protecting the DFB laser, we send the output of the circuit through a 90:10 beamsplitter. The 90% port gets sent to a retroreflector that can be turned on/off to act as unwanted facet reflections. We estimate that the reflected power is 0.4% of the laser power based on the measured insertion loss. The 10% port is sent to a self-heterodyne measurement system to monitor the DFB linewidth at different operating conditions (Fig. 4b). Figure 4c shows the linewidth measurement at different laser frequencies. The achieved sideband suppression of 26.5 GHz (Fig. 4b) can be improved by using a higher-\( \alpha \)-factor microresonator and/or a higher \( f_{\text{RF}} \). The total backward-propagating power is 30 dB lower than the forward-propagating power. Furthermore, an integrated NiCr heater is fabricated with a measured tuning efficiency of 8 nm W\(^{-1}\) (about 125 mW heat power to tune one FSR of 120 GHz) (Fig. 3b,c). Thus, the device can be used to isolate a single-frequency laser by tuning the heater within the broad spectral range (Fig. 2d). Figure 3d shows the relationship between the insertion loss induced by the filter and the sideband suppression ratio based on the intrinsic \( Q \) factor. We measured an insertion loss of 0.9 dB and suppression ratio of 34.0 dB, which is in good agreement with the simulation.

In conclusion, we demonstrate an integrated EO modulator-based optical isolator on TF LN, and verify its ability to protect the phase stability of an edge-coupled on-chip laser. Our device features 48.0 dB isolation ratio.
isolation ratio at the laser frequency, 30.0 dB power isolation, 0.5 dB on-chip insertion loss (1.5 dB with the ring filter) and compatibility with a tunable optical operating wavelength across the C and L bands, using 21 dBm microwave power. To the best of our knowledge, this is the largest optical isolation and the lowest on-chip insertion loss ever demonstrated for an integrated optical isolator. The non-resonant EO device is compatible with a wide range of laser wavelengths. The isolator only requires a counter-propagating single-tone microwave signal and is independent of the input laser power or phase. We overcome the limitations of high insertion loss and low isolation contrast, which typically exist in a non-resonant system due to the lack of Purcell enhancement factor in the light–matter interaction\textsuperscript{25,26}. Our approach benefits from the combination of low insertion loss and high EO efficiency of the integrated LN platform and offers highly competitive performance across all the metrics compared with other on-chip approaches (Methods). We envision further reduction in both on-chip modulator and filter insertion loss to less than 0.1 dB based on the state-of-the-art linear loss of 3 dB m\textsuperscript{-1} on TF LN\textsuperscript{90} and of the laser–LN chip coupling loss to <2 dB through implementation of an antireflective coating on the LN side and direct heterogeneous or hybrid integration of the laser and LN device to reduce the coupling gap. Further improvement of power isolation to 60 dB can be achieved by cascading another tunable ring-based filter. Broadband optical isolation can be achieved based on the interference effect by splitting into multiple modulation paths\textsuperscript{23}. Microwave power consumption can be reduced to 30 mW by reducing the half-wave voltage by half by the implementation of a double-pass phase modulator design\textsuperscript{37} and further down to 13 mW by utilizing a high-performance electrode design\textsuperscript{38} (0.25 dB cm\textsuperscript{-1} GHz\textsuperscript{-0.5}). Finally, the entire laser module could be integrated on the same substrate via the hybrid integration of a semiconductor laser\textsuperscript{39,40}, the LN isolator and an on-chip stable microwave generator. Such a fully integrated, coherent on-chip laser system will be indispensable for applications from optical communication to time–frequency transfer.

### Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41566-023-01227-8.

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We experimentally verify the numerical results using a 4 mm LN waveguide with couplers on either side. The coupling loss between the coupler and lensed fibre is first characterized through the fibre-to-fibre loss, before the input lensed fibre is replaced by the DFB laser to measure the laser coupler loss. The lowest coupling loss is measured to be 2 dB. There is a minimum achievable coupling gap of ∼2 μm from the setup and dice angle of both chips, which agrees with the coupling simulation.

Extended Data Fig. 4 plots the optical spectrum of the DFB laser module (Fig. 4) when the isolator is turned on and off. The microwave operating condition is similar to the condition shown in Fig. 2a.

RIN measurement
We sent the 10% transmission port from the DFB laser and isolator system to a photodetector with a 200 MHz bandwidth followed by a radio-frequency spectral analyser to measure the RIN. Extended Data Fig. 5a shows the RIN over an 8 MHz bandwidth. When the reflection is turned on and the isolator is turned off, we observe beatnotes at harmonics of the external cavity’s FSR in the RIN spectrum (Extended Data Fig. 5a,b), indicating the instability due to the non-negligible reflection. Without the reflection introduced from the fibre reflector path, the RIN is not affected after the microwave driver is turned on (the isolator is on). Therefore, our isolator chip does not add intensity noise to the DFB laser when two chips are edge coupled together. However, when both isolator and reflector are turned on, we observe an increase in RIN. The cause is still under investigation. Regardless, compared with the case of isolator off and reflection on, we do not observe the sharp beatnotes that link to the external cavity formation between the DFB laser and reflector. Therefore, we assume that the isolator protects the laser from reflection, thereby disabling the external cavity formation.

Benchmarking with a fibre-based isolator
The fibre isolator has a fixed isolation ratio of 50 dB. We matched the insertion loss with the chip case and estimate the reflected power to also be at 0.4% of the laser power. Extended Data Fig. 6 plots the RIN measurement for (1) isolator on, reflection off; (2) isolator on, reflection on; (3) isolator off, reflection off; and (4) isolator off, reflection on. Similar to that observed in the LN case (Extended Data Fig. 5), the reflection leads to the sharp beatnote in the RIN spectrum. The isolator successfully protects the RIN of the laser. In the fibre isolator case, all the characterization is in the optical fibres, eliminating the cavity formed between the fibre isolator output and the reflector. This could explain the RIN measurement difference between the LN chip and fibre cases (when both isolator and reflection are turned on). The linewidth measurement is shown in Extended Data Fig. 6b, which is similar to what is observed in the LN chip case (Fig. 4c).

Performance comparison with literature
Extended Data Table 1 lists the detailed performance of this work compared with other integrated isolators including approaches based on magneto-optics12–14, acousto-optics24–26, EO17,19–22 and optical nonlinearity27–30. The performance metrics include isolation ratio, insertion loss, power consumption, operation wavelength and applicability with an on-chip laser.

Data availability
The datasets generated and analysed in the current study are available from the corresponding authors on reasonable request.

Acknowledgements
This work is supported by the Defense Advanced Research Projects Agency HR0011-20-C-0137 (M.Y., R.C., L.H., K.L., L.S., A.S.-A., H.R.G., L.J., M.Z. and M.L.), ONR N00014-18-C-1043 (R.C. and M.Y.) and N00014-22-C-1041 (R.C. and M.Y.), AFOSR FA9550-19-1-0376 (A.S.-A.) and Raytheon Technology A40210 (L.S.). E.P. acknowledges support by the Draper graduate student fellowship program. The device fabrication
was performed at the Harvard University Center for Nanoscale Systems. The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the US government.

Author contributions
M.L. conceived the idea. M.Y. designed the chip with the help of R.C., C.R., L.H. and M.Z. C.R., K.L. and L.H. fabricated the devices. M.Y. and R.C. carried out the measurement and analysed the data with help from E.P., L.S., A.S. and X.R. M.Y. performed the numerical simulations. H.G. and L.J. provided the DFB laser. M.Y. and R.C. wrote the manuscript with contribution from all authors. M.L. supervised the project.

Competing interests
C.R., K.L., L.H., M.Z. and M.L. are involved in developing LN technologies at HyperLight Corporation. The remaining authors declare no competing interests.

Additional information
Extended data is available for this paper at https://doi.org/10.1038/s41566-023-01227-8.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41566-023-01227-8.

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Peer review information Nature Photonics thanks Yeshiaahu Fainman, Juejun Hu and Changzheng Sun for their contribution to the peer review of this work.

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**Extended Data Fig. 1** | **Full measurement setup for the LN electro-optic isolator.** Forward and backward spectra of the isolator are monitored using a tunable laser and 2×2 switch (forward: 1 → 3, backward: 1 → 4) to couple light onto the chip. Polarization controllers are used in both directions to couple light into the transverse-electric (TE) waveguide mode. Spectra are measured on an OSA (optical spectrum analyzer). For III-V laser operation, the DFB laser is edge-coupled directly to the isolator chip. The output is then split between a retroreflector and linewidth and relative intensity noise (RIN) measurement to monitor the behavior of the DFB laser with and without isolation.
Extended Data Fig. 2 | Stability measurement of the isolation ratio. a, The isolation ratio as a function of microwave power. The simulation is performed using the fundamental Bessel function \( J_0(\beta) \), where the microwave power is proportional to \( \beta^2 \). The highest simulated isolation ratio is limited by the finite sampling points. The experimental data shows excellent agreement with the simulation when the microwave power is detuned more than 0.05 dBm (\( \sim 1.1\% \)) from the optimal power. b, The measured isolation ratio over 14 hours at a time interval of 30 seconds. At the beginning, the isolation of 46 dB is achieved at an optical wavelength of 1555 nm and similar microwave setting to that in Fig. 2a & b in the main text (inset: the optical spectrum). To assess the effects of environmental conditions (temperature, air fluctuation, acoustic noise etc), the isolation ratio is monitored as a function of time while keeping all the operation conditions the same. The isolation gradually decreases to 41 dB after 2 hours and stabilizes to a mean value of 41.3 dB with a standard deviation of 0.56 dB over a 12-hour period. The primary reason for the drop in isolation is the polarization variation over time, which is confirmed by the fact that the isolation ratio can be adjusted back to 46 dB after manually adjusting the polarization controller in the setup.
Extended Data Fig. 3 | Coupling between DFB laser and LN chip. a, Quantum well waveguide structure and (inset) simulated output mode of the III-V DFB laser: \( W = 5 \, \text{um}, H_P = 2.5 \, \text{um}, h_P = 500 \, \text{nm}, H_{\text{QW}} = 450 \, \text{nm}, H_N = 4 \, \text{um} \); b, Structure of the LN mode converter at the coupling facet: \( h = 280 \, \text{nm}, w = 250 \, \text{nm} \); c, Simulation of the coupling efficiency between the DFB laser mode and LN facet. An anti-reflective coating is added to the laser structure, as in experiment, to minimize reflection between the laser and the air gap. The minimum coupling gap achievable in our experiment is approximately 2 \, \text{um}, corresponding to about 2 dB coupling loss (indicated by the star). This is loss is further verified experimentally on other LN chips.
Extended Data Fig. 4 | Optical spectral measurement of the DFB laser - LN isolator module. The optical spectrum of the DFB laser module when the isolator is turned on and off.
Extended Data Fig. 5 | Relative intensity noise (RIN) measurement with the LN-chip-based isolator. a, The RIN measurement under four different conditions: 1) isolator on, reflection off; 2) isolator on, reflection on; 3) isolator off, reflection off; 4) isolator off, reflection on. The reflected power back into the DFB chip is estimated to be 0.4% (24 dB) of the laser emission power $P_{\text{laser}}$. The spectral range of the measurement is from DC to 8 MHz. The detector bandwidth is 200 MHz. We observe similar RIN level between the integrated isolator turned on and off while the reflection is turned off. When both reflection and isolator turned on, we observe an increase in RIN. The cause behind this phenomenon is still under investigation since the laser is followed by an extra cavity which is formed between the reflector and chip output facet. When the reflection is turned on and the isolator is turned off, the DFB laser is not protected, and we observe beatnotes at harmonics of the external cavity’s FSR (purple curves in a and b). b, The RIN measurement for the case of isolator off and reflection on. The spectral range of the measurement is from DC to 22 MHz so we could see the higher harmonics of the beatnotes. In this measurement, the FSR of the external cavity is about 7.2 MHz. iso: isolator; ref: reflection.
Extended Data Fig. 6 | The RIN and linewidth measurement using a fiber-based isolator as a benchmark. The isolation ratio is 50 dB. The reflected power is also set at 0.4% of the laser power. a, The RIN measurement over 8 MHz range under four different conditions: 1) isolator on, reflection off; 2) isolator on, reflection on; 3) isolator off, reflection off; 4) isolator off, reflection on. The isolator successfully protects the RIN of the laser. Only in the case of reflection on and isolator off, we observe the beatnote which corresponds to the external cavity FSR (similar to what is observed in the Extended Data Fig. 5). b, The linewidth measurement of the laser. We observe a similar phenomenon as compared to the LN-chip-based isolator case plotted in Fig. 4c. The isolator can protect the single mode operation and the linewidth of the laser. Without the isolator’s protection, the reflection would cause multimode oscillation with spectral spacing equal to the FSR of the external cavity formed between the DFB laser and the fiber reflector. In this measurement, the cavity FSR is 7.2 MHz. iso: isolator; ref: reflection.
## Extended Data Table 1 | Performance comparison with other on-chip isolator approaches

| Platform       | Device                     | Isolation ratio (dB) | Insertion loss (dB) | Power (dBm) | Wavelength (nm) | Tested with on-chip laser | Ref |
|----------------|----------------------------|----------------------|---------------------|-------------|----------------|--------------------------|-----|
| LN (Fig.2)     | EO; waveguide              | 48                   | 0.5                 | 21          | 1553           | No                       | This work |
| LN (Fig.3)     | EO; waveguide + ring filter| 48                   | 1.4                 | 21          | 1552           | No                       | This work |
| LN (Fig.4)     | EO; waveguide + ring filter| 42                   | 2.9                 | 21          | 1556           | Yes                      | This work |
| Ce:YIG/Si      | MO; resonator; WB          | 32                   | 2.3                 | 10          | 1555           | No                       | Ref 13   |
| Ce:YIG/Si      | MO; resonator; WB          | 32                   | 11                  | 15$^*$      | 1550           | No                       | Ref 14   |
| Ce:YIG/SiN     | MO; resonator; PLD         | 28                   | 1                   | 0; magnetic field | 1570           | No                       | Ref 12   |
| Ce:YIG/Si      | MO; waveguide; PLD         | 30                   | 5                   | 0; magnetic field | 1585           | No                       | Ref 15   |
| AlN/Si         | AO; waveguide              | 12                   | 0.6                 | 20.8        | 1523           | No                       | Ref 26   |
| LN             | AO; resonator              | 12.75                | 1.13                | 29          | 1550           | No                       | Ref 25   |
| AlN/SiN        | AO; resonator              | 9.3                  | 0.8                 | 25          | 1550           | No                       | Ref 24   |
| LN             | Second order nonlinearity; waveguide | 18 | 6.6/14$^*$ | 5$^1$     | 1575           | No                       | Ref 30   |
| Si             | Kerr nonlinearity; waveguide | 4 | NA                 | NA          | 1582           | No                       | Ref 29   |
| SiN            | Kerr nonlinearity; resonator | 23 | 4.6                | 20$^2$      | 1550           | Yes$^*$                  | Ref 27   |
| Silica         | Kerr nonlinearity; resonator | 24 | 5                  | 5$^1$       | 1550           | No                       | Ref 28   |
| InP            | EO; waveguide              | 11                   | 2.3                 | 26$^1$      | 1580           | No                       | Ref 21   |
| Si             | EO; waveguide              | 3                    | 11.1                | 24$^1$      | 1556           | No                       | Ref 22   |
| Si             | EO; resonator              | 13                   | 18                  | -3          | 1550           | No                       | Ref 19   |
| GaAs/AlGaAs    | EO; waveguide              | 30                   | 8                   | 18$^1$      | 1550           | No                       | Ref 20   |
| Si             | EO; waveguide              | 3                    | 70                  | 25          | 1555           | No                       | Ref 17   |

EO, electro-optic; MO, magneto-optic; AO, acousto-optic; WB, wafer bonding; PLD, pulse laser deposition; NA, not available

$^\dagger$ Extracted from publication
*Including 3.7 dB loss per facet
$^\ddagger$ Optical power
$^\wedge$ Power dependent
$^a$ Only backward transmission is tested