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Photonic technologies for autonomous cars: feature introduction

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Photonic technologies that support the low cost manufacturing needed for automotive sensors have experienced explosive developments in recent years. To date most commercially available lidar system have been direct detection time-of-flight (ToF) sensors operating at 905 nm using mechanical mirrors for beam steering. However, these sensors suffer from important drawbacks. One issue is eye-safety, which limits maximum laser powers and hence operating range. Direct detection systems must also content with potential interference issues when lots of cars operate lidar systems simultaneously. In addition, mechanical scanners are frequently bulky and may be difficult to integrate within the form factors allowed by modern vehicles.

Optical phase arrays (OPAs) integrated with gratings, realized with photonic integrated circuit (PIC) technology, offer an attractive approach to miniature the scanner function and eliminate mechanisms. To leverage mature PIC technologies at telecommunication wavelengths (1.3 to 1.6 µm), the center wavelength of chip-based lidar is usually shifted from 905 nm to the longer wavelength window. This also alleviates concerns about eye-safety. Furthermore, the miniaturized size of PIC chips promises to embed large numbers of them in the peripheries of vehicles, which can provide a wide field of view (FOV) without significantly affecting the appearance of cars.

In this feature issue, Weiqiang Xie *et al.* demonstrates a novel OPA based on a Silicon photonic (SiP) platform. It is composed of star coupler heterogeneously integrated with III-V phase shifters, and an array of gratings. Compared with previously reported Si-photonic OPAs, this technology has the advantage of much lower power consumption and higher switching speed. This is because the III-V phase-shifter can be operated under reverse bias with nearly zero leakage currents and little residual amplitude modulation (RAM). This is in contrast to reverse biased Si junctions, which have much higher leakage currents and high RAM; and also in contrast to common thermal phase shifters which typically draw tens of mW each to achieve 2π phase shifts.

An alternative way to produce scanning is to integrate an optical switch array with optical gratings (optical antenna) for different diffraction angles. Daisuke Inoue *et al.* have demonstrated such a scanner on a SiP platform. Using an optical ring resonator as a switch, much smaller power consumption for beam steering can be realized compared to previously reported SiP OPA. On the other hand, in order to reduce the power-consumption of traditional thermal phase-shifter on SiP platform for OPA application, Manuel Mendez-Astudillo, *et al.* have demonstrated a novel phase-shifter, which combines the structure of silicon-on-insulator (SOI) optical waveguide with a built-in resistive heater. By directly injecting current into SOI waveguide, faster switching speed and lower power consumption than those of traditional thermal phase-shifter have been achieved.

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Aside from electrical power consumption in phase shifters, optical insertion losses (radiation efficiency) and FOV are both critical issues in the performance of OPA for lidar applications. Yu Zhang *et al.* have demonstrated a novel SiP based OPA, which can greatly enhanced (double) the radiation efficiency and provide a FOV as wide as 70° by embedding DBR pairs below the 2-D grating and using optimized pitch size apodized gratings, respectively.

As noted above, 905 nm wavelength is an interesting spectral regime for lidar application. In order to enable operation wavelength of OPAs on SiP platforms at 905 nm, Nicola A. Tyler *et al.* have demonstrated a Si_3N_4/SiO_2-based OPA platform. They demonstrate that this enables elimination of undesired photo-absorption in the silicon core layer of SOI waveguides. The ranging and detection concepts of lidar can also be extended to the visible wavelength regime for so called smart headlights. Compared with light-emitting diodes (LEDs), laser diodes are preferred for smart headlights due to the coherent and narrow laser output beam profile being essential for long range detection. However, the high brightness of laser beam may result in reliability issues of phosphors used for visible white-light generation. Yung-Peng Chang *et al.* have demonstrated an advanced headlight module employing highly reliable glass phosphor for such application.

Compared with lidar, radar technology generally has a longer operating range and is less sensitive to weather conditions. However, this comes at the expense of reduced spatial resolution. One way to increase resolution is to increase the aperture size of the antenna. However, as in the case of lidar systems with mechanical scanning mirrors, large antennas cannot be fitted within the streamlined shape of vehicles. Stefan Preussler *et al.* have a proof-of-concept demonstration of a photonically synchronized large aperture radar for self-driving car. By using a common laser source to synchronize multiple miniaturized radiation units installed in the periphery of a vehicle, coherent beam forming with a large aperture size can be realized.

Lidar, radar, and video sensors produce huge amounts of real-time high-resolution data. To handle these data streams high-speed data transmission through an in-car fiber network is highly desirable. Compared with bulky coaxial cable, optical fiber has the advantage of low weight and immunity against electromagnetic interference, which are important issues, especially for electric vehicles (EVs). Xiaoyang Cheng *et al.* have demonstrated real time video data transmission based on a novel polymer based optical modulator and single-mode fiber at telecommunication wavelengths.

While lidar and radar sensors attract most of the attention when discussing photonics in the automotive context, high-quality video is also critically important. Producing clear imagery is important but tends to also be computationally expensive. Chia-Chi Tsai *et* al. have demonstrated a novel video dehazing algorithm to greatly reduce the computational complexity of the traditional "Dark Channel Prior" (DCP) approach. Success of the method is demonstrated by the Renesas R-car M2 resolution video.

In summary, the development of photonic technologies for autonomous cars is nowadays one of the most competitive research areas among those devoted to the industry of self-driving car. Compared with the long development history of radar and camera technologies, time for the development of lidar related technologies is much shorter, but its continuous performance improvements promise to aid in passenger safety in autonomous vehicles.

I hope that the present Feature Issue may serve not only as a summary of different research lines, but also that it may encourage further work in this exciting field.

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