Response to the 1st Stakeholder Consultation – Questionnaire for indium phosphide (CAS 22398-80-7; EC 244-959-5)

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About Lumentum

Lumentum (NASDAQ: LITE) is a market-leading manufacturer of innovative optical and photonic products enabling optical networking and commercial laser customers worldwide. Lumentum's optical components and subsystems are part of virtually every type of telecom, enterprise, and data center network. Lumentum's commercial lasers enable advanced manufacturing techniques and diverse applications including next-generation 3D sensing capabilities. Lumentum is headquartered in Milpitas, California with R&D, manufacturing, and sales offices worldwide. For more information, visit www.lumentum.com.

Abbreviations and Definitions

DCI	Data Center Interconnects. Optical fiber links between data centers.
DWDM	Dense Wavelength Division Multiplexing. Refers to transmitting multiple data channels on a single optical fiber using multiple carrier wavelengths within the C-band, S-band or L-band that are closely spaced in wavelength or optical frequency (typically, 50-100 GHz spacing).
EDFA	Erbium Doped Fiber Amplifier. A device that amplifies the optical signal using a long length of silica fiber doped with erbium and optically pumped to provide gain.
ICT	Integrated Coherent Transmitter. A fiber-coupled packaged component with an integrated laser and IQ modulator which forms a coherent transmitter
IC-TROSA	Integrated Coherent Transmitter Receiver Optical Subassembly. A fiber-coupled component which includes both the transmitter and receiver photonic integrated circuits as well as driver and transimpendance amplifier electronics.
IQ	In-phase / Quadature phase. Referring to the modulation or encoding of an optical signal for coherent communications, in which the signal can be decomposed into two superimposed time-varying signals that are separated by 90 degrees phase shift in the optical carrier frequency.
ITLA	Integratable Tunable Laser Assembly. A fiber-coupled packaged tunable laser source with associated control electronics which produces a continuous wave output that can be used with a separate modulator component or as a local oscillator in a coherent receiver.
MZ	Mach-Zehnder modulator. A device that can modulate the amplitude or phase of light through the constructive or destructive interference of light propagating in two or more waveguides connected by a splitter and combiner. Application of a voltage-induced phase shift on either or both waveguides allows an electrical signal to be encoded onto the optical carrier wave.
O-band, S-band, C-band, L-band	Spectral bands corresponding to windows of favorable transmission properties in silica optical fiber. Wavelength ranges are approximately as follows: • O-band: 1260 – 1360 nm • S-band: 1460 – 1525 nm • C-band: 1527 – 1569 nm • L-band: 1570 – 1610 nm

	Semiconductor Optical Amplifier. A device that amplifies the optical signal through injected current and can be readily integrated in a photonic integrated circuit.
TOSA	Transmitter Optical Sub-Assembly. A fiber-coupled packaged laser transmitter component.

1. Applications in which indium phosphide is in use

a) Please provide information concerning products and applications in which the substance is in use.
i. In your answer please specify if the applications specified are relevant to EEE products and applications or not.

ii. Please elaborate if substitution of the substance is already underway in some of these applications, in relation to the properties for which indium phosphide is used (for example semiconductor and photovoltaic properties) and/or in relation to specific applications in which it is used (for example critical communication components),

iii. Where relevant, please elaborate which chemical (on the substance level) or which technology (elimination of the need to use InP) alternatives may be relevant for this purpose.

Indium phosphide (InP) is used in a variety of semiconductor devices that are critical for fiber optic communications equipment that is covered by EEE category #3 “IT and telecommunications equipment” of the RoHS Directive. Tunable lasers, InP modulators, fixed wavelength O-band lasers, High power 1480 nm pump lasers used in EDFA, Raman pump lasers (1420 nm to 1495 nm wavelengths), and photodiode arrays (O-band, C-band, L-band, S-band) are all InP-based. In all cases, the InP-based active material of the above devices produces light emission, detection, or modulation at wavelengths compatible with low dispersion or low loss in optical fiber which enables much higher data rates (for a given distance) or much longer distances (for the same data rate) than can be achieved with GaAs. This is summarized quantitatively in the following table.

Table 1: Link distance at 100 Gb/s for GaAs and InP-based component technology

Fiber Communications Band	Silica Fiber type	Link distance at 100 Gb/s	Component technology
850 nm	Multi-mode	150 m	GaAs-based
1260-1360 nm (O-band)	Single mode	2 km	InP-based
1527-1570 nm (C-band)	Single mode	>80 km	InP-based

The table below provides detailed overview of InP applications in fiber optic communications and InP alternatives.

Table 2: InP applications in fiber optic communications and InP alternatives.

InP Device	Where used	Application	Alternatives
Tunable lasers	ITLA modules	Light source for DWDM coherent fiber optic communications systems. Typically used with an external modulator and integrated into optical modules or line cards for Metro and Long Haul telecom transmission applications.	No viable alternative for semiconductor lasers.
Tunable lasers with integrated Mach-Zehnder (MZ) modulators	10G TOSAs for TXFP modules	10G pluggable modules for DWDM Metro and Long Haul fiber optic communications systems.	Alternate modulator technologies exist, but there is no viable alternative for the laser (e.g. InP laser co-packaged with Silicon Photonic modulator). Severe size constraint also demands monolithic integration of the laser and MZ on a single material system (InP).
Narrow linewidth tunable laser with integrated IQ modulators and SOA's	100G to 600G ICT and IC-TROSA components for integration into telecom transmission modules	100G - 600G transponders and transceivers for high capacity DCI, Metro and Long Haul DWDM fiber optic communications links	No viable alternative for tunable laser source. Modulator can be implemented in SiP or LiNbO3 and co-packaged with the InP laser. LiNbO3 is physically much larger and requires higher drive voltage. Silicon Photonic modulators are more complex to control and have much higher losses, as well as higher drive voltage. Neither LiNbO3 or Silicon Photonic modulators allow integration of SOA amplification, requiring bulky and expensive external amplification in high power applications such as long haul and metro networking.
Standalone InP modulators	No current Lumentum program, but other vendors implement this technology for HB-CDM components	Displacing LiNbO3 modulators in high performance fiber optic communications applications from 100G to 600G due to smaller footprint, lower drive voltage and ability to integrate optical amplification monolithically with the modulator structure.	LiNbO3 modulators (physically significantly larger, higher drive voltage requirements). Silicon Photonic modulators (similar size but more complex to control, higher losses, and higher drive voltage requirements). Neither of these alternatives allow the integration of SOA optical amplifiers monolithically with the modulator structure.
Fixed wavelength O-band lasers (directly modulated)	Client and DCI pluggable modules from 10G to 200G such as XFP, SFP+, CFP2, CFP4	Short reach (<10 km) high volume optical interconnect within a data center or to connect client services to telecom transmission equipment using single mode fiber	VCSEL technology can be used for the shortest reach applications (usually on multi-mode fiber). Some efforts have been made to productize 1310 nm VCSELs, but so far unsuccessfully due to insufficient optical output power in the fiber.
Fixed wavelength O-band lasers with integrated external modulators (EML or MZ)	Longer reach 10G client and DCI interfaces (40 and 80 km) as well as high speed arrays for 100G and 400G modules	Intra data center switch interconnect, and connecting client services and routers to telecom transmission equipment.	No alternative to InP.
High power 1480 nm and Raman pump lasers (1420 nm to 1495 nm wavelengths)	Pump laser components used in EDFAs and Raman fiber optic amplifiers	Optical amplifiers enabling long haul fiber optic transmission	No alternative to InP.

InP Device	Where used	Application	Alternatives
O-band, C-band, L-band Photodiode arrays	Photonic detectors used in optical receivers for all single mode fiber optic applications from data center interconnect to Long Haul	All optical interconnects from 10's of meters to thousands of km	Germanium-on-Silicon waveguide photodiodes are potential replacements for InP-based waveguide photodiodes in O-band and C-band (but not L-band), where the optical beam is edge-coupled to the die. Germanium is not suitable for component architectures requiring normal-incidence surface or backside illumination which have looser alignment tolerances.
S-band photodiode arrays	Short reach applications using multimode fiber interconnect	Intra-data center server and switch connectivity	Potential alternatives such as Germanium, Indium Gallium Arsenide multiple quantum well and Indium Gallium Arsenide Nitride have much lower performance and are not suitable replacements for InP.

b) Please specify if you are aware, if aside from actual use of the substance, it may be re-introduced in to the material cycle through the use of secondary materials.

Lumentum is not aware if InP may be re-introduced into the material cycle through the use of secondary materials.

c) Please specify in which applications indium phosphide is used as a material constituent, as an additive or as an intermediate and what concentration of indium phosphide remains in the final product in each of these cases (on the homogenous material level).

InP is used as a main constituent material in the InP-based semiconductor devices. Based on the laser dies manufactured by Lumentum the average concentration of InP in the homogenous material ranges from 95% to 98%. The mass of a single die is 0.03 mg to 1.1 mg.

2. Quantities and ranges in which indium phosphide is in use

a. Please detail in what applications your company/sector applies indium phosphide and give detail as to the annual amounts of use. If an exact volume cannot be specified, please provide a range of use (for example – 10-100 tonnes per annum).

Based on the annual wafer production, scrap and the yield Lumentum puts on the market globally about 1 kg of InP in its dies that ultimately are used for EEE. However, the actual use of InP in the fabrication process itself is higher as a function of a die yield on an individual wafer and a wafer scrap.

b. Please provide information as to the ranges of quantities in which you estimate that the substance is applied in general and in the EEE sector in the EU and globally.

Lumentum estimates its global market share of InP dies for optical communication to be at 2% to 5%. Since Lumentum puts annually 1 kg of InP with its dies on the market, globally it would be 20 kg to 50 kg of InP for the total global optical communication market. Lumentum estimates that EU represents 25% of the global market share in the optical communication. These market share estimates are based on market share reports from OVUM, Lightcounting and Cignal AI. Based on that Lumentum estimates that 5 kg to 12.5 kg of InP are put annually on the EU market with the optical communication equipment.

c. If substitution has begun or is expected to begin shortly, please estimate how the trend of use is expected to change over the coming years.

Lumentum does not expect any substitution of InP in optical communication products.

3. Potential emissions in the waste stream

a. Please provide information on how EEE applications containing indium phosphide are managed in the waste phase (with which waste is such EEE collected and what treatment routes are applied)?

As a manufacturer of optical components and subsystems for the optical communication equipment Lumentum does not have a visibility into the InP waste management from the EEE waste. Because InP devices are attached to PCBAs, Lumentum assumes that they follow the PCBA recovery process.
Lumentum generates InP waste during the laser die fabrication therefore, Lumentum's InP waste stream management process is described below.

Lumentum's InP scrap wafers are generally mixed with other type of scrap wafers and waste materials from the fabrication process that contain precious metals like gold, palladium and platinum. This material is send for the recovery of precious metals to different refiners which may apply different recovery methods:

- chemical strip of surface metals
- smelting to separate precious metals
- ball-milling and smelting to separate and recover precious metals.

Lumentum reached out to one of its main refiners in USA to clarify the InP material stream during the processing. The refiner was not measuring indium content in its mixed materials nor was the refiner aware of any smelter measuring indium content or recovering indium from its material. The reason for that is a relatively low price for indium (~$0.30 per gram of indium versus ~$40 per gram of gold.)

Few years ago Lumentum conducted a feasibility study of a separate InP scrap material treatment. Lumentum collected separately InP scrap wafers over one year timeframe in order to accumulate sufficient amount of InP scrap material that could be treated separately. The separate treatment of InP scrap wafers turned out not to be economically viable as the labor needed to optimize the separate recovery turned out to be more costly than the value of the recovered material.

b. Please detail potentials for emissions in the relevant treatment processes.

InP-based scrap wafers contain small amount of arsenic and are mixed with other arsenic bearing materials therefore, the process is managed to meet strict requirements for arsenic treatment and disposal standards. Lumentum does not have data of emissions from the separate treatment of InP scrap wafers.

4. Substitution

a. Please provide details as to the substitution of indium phosphide:
i. For which applications is substitution scientifically or technically not practicable or reliable and why.

Indium phosphide, and alloys of indium phosphide with related compounds such as InGaAsP or InGaAlAs, which can be grown epitaxially as thin layers of crystalline semiconductor on InP substrates, is unparalleled for use within transmitters or receivers in fiber optic communications systems at 1.3 um or 1.55 um wavelength ranges. The reason for this is several-fold:

- Wafer-scale fabrication enables volume low-cost production. InP (and InGaAsP or InGaAlAs) is a single crystal semiconductor (like silicon) and can be fabricated using similar semiconductor processing techniques and doped to form electrically active structures like pin diodes which can be metalized with electrical contacts and forward or reverse biased to control current flow or electric field.
- InP and related materials enable efficient laser operation and generation of light, efficient modulation of the intensity or phase of light at high speed to encode an optical signal, and efficient detection of light to convert that signal to the electrical domain. This comes about because the material has a direct bandgap (unlike silicon). Direct bandgap semiconductor implies that the intrinsic interaction strength between electrons in the material and photons (light) is several orders of magnitude stronger than for an indirect bandgap material like silicon.
- InP and related materials enable monolithic functional integration, smaller size, and therefore higher efficiency optical transceivers, due to having controllable optical properties than can be tailored to meet the requirements of the specific optical communications application as well as through integration of multiple material compositions on the same chip or substrate. The material has a direct bandgap energy, and corresponding wavelength, which can be adjusted through material alloy composition to match the transmission windows of single mode optical fiber. In particular, photonic devices can be designed to function in the O-band (near the fiber dispersion minimum of 1310 nm wavelength, important for shorter link distances at high speed within the data center or central office) or the C-band (near the minimum loss wavelength of 1550 nm, important for longer-distance communication systems within a metropolitan region or between cities/countries). Importantly, multiple semiconductor material compositions with varying bandgap energies can be integrated within a single device or across a wafer or die to enable more efficient operation and to combine multiple device functions on a single chip. This is achieved by adjusting the precise ratios of indium to gallium, arsenic

to phosphorous, or gallium to aluminum in InGaAsP or InGaAlAs alloys to achieve the desired bandgap while still maintaining a lattice constant that is compatible with single-crystal epitaxial growth on an InP substrate. In addition, the large relative refractive index difference available to InP devices enables very small waveguide dimensions (~1 um) and hence highly compact device or chip dimensions. This is not the case for lithium niobate waveguides, silica-on-silicon waveguides, or free space optics which may be 10 or 100 times larger.

A suitable replacement material needs to have a direct bandgap that is compatible with 1.3 um or 1.55 um. For lasers, the dilute nitride system GaInNAs (deposited epitaxially on GaAs substrates) has been researched for more than twenty years but has faced fundamental epitaxial growth and reliability issues which prevented commercial deployment [1]. Likewise alloys of germanium and tin (GeSn) with Sn composition of ~10% have exhibited direct bandgap and may be grown on Si substrates, but laser oscillation has so far been demonstrated only at low temperature (110 K) under optical pumping [2],[3]. In addition, the emission wavelength is beyond 2.5 um, making it unsuitable for optical fiber transmission.

ii. For which applications is substitution underway? Please specify in this respect which alternatives are available on the substance level (substitution) and which are available on the technological level (elimination). For example, which alternatives can be applied instead of indium phosphide used in solar cells and in semiconductor applications (e.g. gallium arsenide)

Silicon nano-wire waveguides fabricated on silicon-on-insulator substrates is being actively investigated as a possible replacement for a limited set of InP-based devices. One example is the Mach-Zehnder modulator. In such devices, the Mach-Zehnder interferometer structure converts the time-varying voltage signals applied to the modulator electrodes and underlying semiconductor waveguide material into an equivalent optical phase shift, and interference between the two arms of the interferometer results in modulation of the phase or intensity of the output light. The physical phenomenon creating this phase shift differs between InP and Si. InP-based devices rely on the quantum confined Stark effect (QCSE) in a thin multilayer stack of InGaAsP or InGaAlAs which forms the waveguide on the InP substrate, and which has a bandgap wavelength near the operating wavelength. Si-based devices rely on the free carrier plasma effect (FCP) in doped Si waveguides. The strength of the phase shift per unit voltage is considerably weaker for FCP compared to QCSE. To compensate for this, Si-based designs are

- 2 to 5 times longer, increasing optical loss and reducing modulation bandwidth, or
- driven at significantly higher voltages (1.5-2 times), increasing the power dissipation in the drive electronics, or
- under-driven, never able to fully reach an “on” state, which effectively means increased optical loss.

The performance tradeoff is summarized quantitatively in the following table. The modulation bandwidth per voltage required to achieve 180 degree phase shift (Vpi) is the relevant figure of merit, and it is ~4 times higher in InP than for Si.

Table 3: Performance comparison of InP and Si based designs

Parameter	**InP**	**Si**
Bandwidth/Vpi	16-20 GHz/V	4-5 GHz/V
Driver Voltage	2-2.8V	~4V

Due to this large disparity in bandwidth per voltage, Si-based modulators may employ under-drive or related compensating techniques to maintain drive voltage at a barely acceptable level, but this comes at the expense of additional insertion loss and corresponding reduction in efficiency in both the modulator and the drive electronics. However, this disparity becomes problematic as symbol rates scale from 32 to 64 Gbaud to support data rates scaling to 400-600 Gb/s. Therefore, substitution by Si may be limited to low symbol rates (25 Gbaud) combined with parallel single-mode fiber and short distance.

Photodetection affords the most opportunity for substitution. InGaAs active material on InP provides the highest responsivity and quantum efficiency owing to its direct bandgap wavelength of ~1.65 um. This makes it the material of choice for both surface-illuminated or waveguide photodetector geometries. Germanium can be a suitable substitute only in waveguide geometries when integrated with silicon nanowire waveguides on Si substrates, because its lower absorption coefficient can be compensated by increased device length. Nonetheless, germanium’s ability to absorb and thereby detect light drops off rapidly beyond the long wavelength end of the C-band at ~1570 nm. In particular, responsivity drops by more than a factor of two at the far end of the L band (1610 nm). Conversely, Ge has more potential at shorter wavelengths such as the O-band (1310 nm). Substitution is limited to optical component architectures that edge-couple light from optical fiber to the waveguide. In contrast, normal incidence photodiode geometries, which are the most common solution at lower bitrates and which provide advantages in alignment tolerance, power handling capability, and polarization independence, are not compatible with substitution by Ge-on-Si waveguide photodiodes.

iii. What constraints exist to the implementation of the named substitutes in a specific application area (provide details on costs, reliability, availability, roadmap for substitution, etc.).

As detailed in 4a ii, availability of substitutes with equivalent performance and reliability to existing InP-based solutions limit adoption as follows:

- Laser: Substitute semiconductor laser materials that are compatible with operation at wavelengths of 1.3 um and beyond are highly constrained. Development of a GeSn-based laser is still at the basic materials research stage of development. Early reports suggest that the required amount of Sn for a direct bandgap result in lasing wavelength outside of the 1.3-1.6 um single mode fiber transmission window. No deterministic roadmap exists for replacement. GaInNAs on GaAs was also previously proposed as a potential substitute [1]. Despite much research activity over the past 20 years, GaInNAs lasers have not been commercially deployed to our knowledge, and our own internal studies have revealed device reliability to be the primary impediment.

- Modulator: In limited cases an alternative exists in silicon but with performance limitations on bandwidth and insertion loss. This limits substitution to applications where either the symbol rate is low (25 Gbaud), or where erbium-doped fiber amplifiers can be added in line to boost the signal, which increases the power dissipation and limits the compactness of the transceiver.
- Detector: In limited cases, namely high bandwidth edge-coupled applications, a Ge-on-Si waveguide photodiode can be used as a direct substitute for InGaAs-on-InP. Package architectures that require surface illumination, for reasons of cost, alignment tolerance, or power handling capability, will not have this option. In addition, Ge-based waveguide photodiodes suffer from performance limitations at L-band wavelengths due to reduced responsivity.

5. Socio economic impact of a possible restriction

Please provide information as to the socio-economic impacts if indium phosphide is to be restricted under RoHS. Please specify your answers in relation to specific applications in which the substances are used and/or in relation to the phase in of specific alternatives in related application areas. Please refer in your answer to possible costs and benefits of various sectors, users, the environment, etc. where possible; please support statements with quantified estimations.

The restriction of indium phosphide would significantly impact the backbone of the fiber-optic network for telecommunication and internet, the connections to the cellular network, cloud data centers and enterprises. Without InP the communication technology would move back to copper based network, which would not allow internet to function and a long distance connectivity would not be possible. As a result the fiber-optic network would need to be replaced with other type of communication network like a radio-based or satellite based communication network, which currently are not sufficiently expanded to provide consumers currently existing telecommunication services. Table 4 summarizes impact of InP devices on consumers and services, which would not be possible with the restriction of InP.

Table 4: Impact of InP devices on consumers and services

InP Device	Where used	Impact of InP device on consumer	Services impacted
Tunable lasers	ITLA modules	Tunable lasers integrated into ITLAs are used as the light sources for Long Haul and Metropolitan fiber-optic communications networks (e.g. those operated by Orange, Deutsche Telecom) to provide very high data capacity connectivity: - Between countries for Submarine networks - Between cities for long haul networks - within metropolitan areas for Metro networks. All internet traffic between cellular networks, consumers, businesses and datacenters are multiplexed up to high aggregate data rates and transported over these networks to form the internet.	Backbone fiber optic network
Tunable lasers with integrated Mach-Zehnder (MZ) modulators	10G TOSAs for TXFP modules	As above for tunable lasers. 10G pluggable DWDM transceivers are typically used closer to the edge of networks where the highest capacity is not needed, for example connecting cellular networks to the main backbone network, or within cable TV networks where data is carried from the backbone into the neighborhoods.	Backbone fiber optic network, Connections to cellular network
Narrow linewidth tunable laser with integrated IQ modulators and SOA's	100G to 600G ICT and IC-TROSA components for integration into telecom transmission modules	As above for tunable lasers. These devices represent the cutting edge of optical networking technology where the modulation function is integrated onto the tunable laser, as well as optical amplification with SOA technology. This results in smaller, faster and ultimately cheaper optical networking equipment and allows network operators to keep up with ever increasing traffic demands at reasonable cost and without increasing the space and power requirements of the networking equipment.	Backbone fiber optic network
Standalone InP modulators	No current Lumentum program, but other vendors implement this technology for HB-CDM components	The highest performance long reach and high capacity networking applications require very linear, low loss modulator components. Traditionally these modulators have been made from Lithium Niobate (LiNbO3). Recent advances in technology have allowed equivalent performance to be achieved from InP modulators, which are significantly smaller and require lower drive voltage than LiNbO3, allowing network equipment manufacturers to keep up with ever increasing traffic demands within the size and power footprints of existing communications network nodes.	Backbone fiber optic network
Fixed wavelength O-band lasers (directly modulated)	Client and DCI pluggable modules from 10G to 200G such as XFP, SFP+, CFP2, CFP4	This type of laser is used in optical transceivers used to connect client services to the metro or backbone network. They are also used within data centers to connect severs and switches together. Since they are used near the edge of the network the volume is very high.	Connection to the backbone network, cloud data centers, enterprise etc.
Fixed wavelength O-band lasers with integrated external modulators (EML or MZ)	Longer reach 10G client and DCI interfaces (40 and 80 km) as well as high speed arrays for 100G and 400G modules	This is a higher performance version of the line above, allowing longer reach and faster connectivity	Conection to the backbone network, cloud data centers, enterprise etc.
High power 1480 nm and Raman pump lasers (1420 nm to 1495 nm wavelengths)	Pump laser components used in EDFAs and Raman fiber optic amplifiers	Optical amplifiers are used in networks to boost the signal power to allow a signal to go further, or to propagate through a high loss element like an optical switch. Optical amplifier technology has revolutionized fiber optic networking since without it, the signal must be regenerated back to electrical data, recovered, and then re-transmitted back as optical data. In a DWDM network with many wavelengths of data on the fiber this is orders of magnitude more expensive than optical amplification.	Long haul and metro networks

InP Device	Where used	Impact of InP device on consumer	Services impacted
O-band, C-band, L-band Photodiode arrays	Photonic detectors used in optical receivers for all single mode fiber optic applications from data center interconnect to Long Haul	Photonic detectors are needed at all levels of the optical network (submarine, long haul, metro, client, data center interconnect, etc.) to detect the incoming photons of the optical signal and turn these into electrons that can be amplified and process to recover the original electrical data stream.	All of the above
S-band photodiode arrays	Short reach applications using multimode fiber interconnect	As above. Although the laser in the transmitter for 850 nm multi-mode applications can be made out of GaAs instead of InP, at high data rates (100 Gb/s or above) the receivers still use InP.	All of the above

References

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