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Fibre optics: Forty years later

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Abstract. **This paper presents a brief overview of the state of the art in fibre optics and its main applications: optical fibre communications, fibre lasers and fibre sensors for various physical property measurements. The future of fibre optics and the status of this important area of the modern technology in Russia are discussed.**

Keywords*: optical fibre, optical fibre communications, fibre sensors, fibre optics.*

1. Introduction

Fibre optics emerged in the 1950s as an area of optics dealing with the properties and applications of glass fibres. At that time, the absorption of light in optical fibres was very high, ~ 1000 dB km^{-1} or more, and light would drop in intensity almost twofold after travelling just ~ 1 m of fibre. Such fibres were of limited utility for practical application, and fibre optics developed very slowly.

The advent of lasers in the early 1960s led to intense research interest in the possibility to transmit information through the atmosphere using laser light. However, the first experiments showed that this medium was unsuitable for transmitting optical information over long distances.

In 1966, Kao and Hockham [1] examined the feasibility of using glass fibres as a transmission medium in optical communication systems from the viewpoint of achieving sufficiently low optical loss and high transmission capacity. Their theoretical and experimental studies showed that the high optical loss in glass was due to high impurity concentrations, suggesting that the optical loss in silica fibres might be reduced to well below 20 dB km^{-1} by improving the glass manufacturing process. Optical fibres might then exceed radio and coaxial cable systems in transmission capacity.* Their results stimulated intensive effort aimed at creating low-loss glasses and glass fibres. In 1970, Corning developed a process for the fabrication of silica-based fibres with a loss of 20 dB km^{-1} at 633 nm [2], which opened up real possibilities for building optical communication systems.

Owing to that achievement, fibre optics became one of the most rapidly growing fields of modern science and technology, vital for modern society, and entered a new stage in its development. Starting in the early 1970s, in many countries, including the Soviet Union [3], considerable effort was concentrated on the technology of low-loss optical fibres and their optical, mechanical, and other properties. Extensive research in this area was driven by the prospect of creating optical fibre communication systems with data rates several orders of magnitude higher than those in radio communications.

The efforts in this direction culminated in a family of optical fibres, including single-mode, step- and graded-index multimode, dispersion-shifted (zero group velocity dispersion in the 1.5-μm region), dispersion-decreasing, and other fibres. The optical loss in the fibres was reduced to the lowest possible level, below 1 dB km^{-1} in the spectral range 1 – 1.7 μm, and their strength was brought to a level above that of steel wire of the same diameter. In 1980, the first commercial optical fibre communication systems were launched. They operated in the range 0.8 – 0.9 μm and had a data rate of 45 Mbit s^{-1}.

The next generation of optical fibre communication systems utilised laser light with a wavelength of 1.31 μm, which falls in the near-zero dispersion range of silica-based fibres. This enabled data transmission at 500 Mbit s^{-1}. Modern optical fibre communication systems typically exploit the spectral range around 1.55 μm, where the optical loss has the absolute minimum (~ 0.16 dB km^{-1}).

In 1988, the first transatlantic undersea fibreoptic cable system, connecting Europe with North America, was installed. The successful cable laying and subsequent operation showed reliability of the entire system and all its components.

In addition to studies directly related to the development of optical fibre communications, extensive basic research was focused in many centres on glass optical fibres as very interesting physical systems. Indeed, varying the core composition and refractive index profile of fibres enables their transmission spectrum, nonlinearity, dispersion and other parameters to be tuned in rather wide ranges. The low optical loss and small core diameter allow one to examine the interaction of the core material with laser light travelling a long distance. Owing to these unique properties of glass fibres, a new area of laser physics and optics has emerged and is rapidly growing: nonlinear fibre optics. Because of space limitations, this paper does not examine in detail the extremely interesting results of basic and applied research in

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[*] Charles K. Kao was awarded half of the 2009 Nobel Prize in physics for those works.

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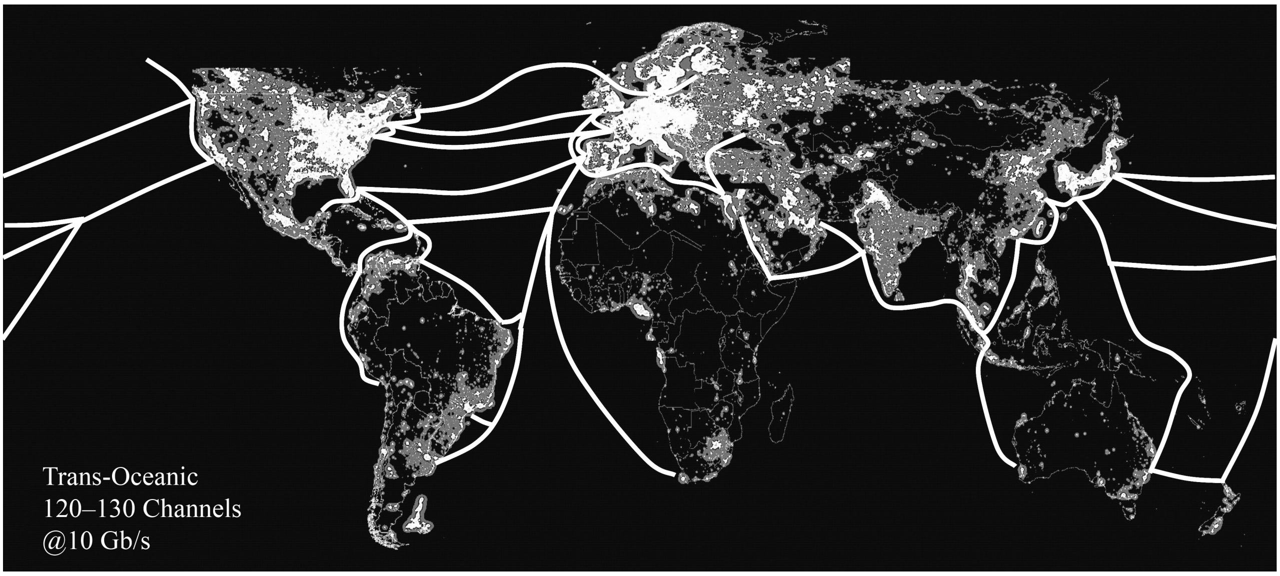

Figure 1. Transoceanic optical fibre communication lines (Alferness R.C., Optical Communications – A View into the Future, Eur. Conf. on Optical Communication, Brussels, 2008).

this direction, which can be found in a number of reviews on nonlinear fibre optics (see e.g. Refs [4 – 6]).

The focus of this paper is on the key applications of fibre optics, the main results reported to date and future prospects in this area.

2. Main applications of optical fibres

The main applications of fibres are optical fibre communication, fibre lasers and fibre sensors.

In addition, optical fibres are widely used to deliver laser radiation to various objects, in particular, in materials processing, medicine, and biological, physical, chemical and other experiments.

2.1 Optical fibre communication

Optical fibre communication was the key driving force behind the creation of glass optical fibres with low optical losses, α, in the near-IR spectral region ($\alpha \leqslant 0.3$ dB km^{-1} in the wavelength range 1.35 – 1.75 μm, with $\alpha_{\min} \leqslant 0.2$ dB km^{-1} at 1.55 μm).

Since 1980, when the first optical fibre communication systems were commercialised, several generations of such systems have succeeded one another. Currently, the per-fibre capacity in commercial communications networks, including undersea transoceanic fibre lines, is 1 – 2 Tbit s^{-1}. Pilot systems have demonstrated a data rate of 25 Tbit s^{-1}. Use is made of wavelength-division multiplexing, where a hundred channels differing in carrier wavelength are combined within one fibre, with a channel data rate of 10 Gbit s^{-1}. The spectral range of information transmission in such systems is 80 nm in width (1.53 – 1.61 μm), which is set by the gain band of erbium-doped fibre amplifiers.

All the continents are connected to one another by undersea fibreoptic cables, with a total length of 600 000 km (enough cable to wrap around the Earth 15 times) (Fig. 1). The total length of fibres in the terrestrial optical communication systems is 10^9 km. The figure is expected to double by 2015. At present, the annual world production of optical fibre exceeds ~ 100 million km.

The past few years have seen explosive growth in a new optical fibre communication technology: broadband (up to 10 Gbit s^{-1}) Internet access at home. A number of countries are actively deploying the Fibre to the Home (FTTH) Programme.

Figure 2 illustrates the growth dynamics of the number of households connected to FTTH networks. The leader is Japan, with 15 million FTTH subscribers in 2008. The technology has been successfully implemented in the United States and South Korea, and more recently in China. The European countries severely lag in deploying FTTH, which causes anxiety in the European Union because this programme has important social implications. A wholesale domestic broadband network can deliver massive social benefits, including tele-education, telemedicine, teleworking etc. The global number of Internet users has passed the one-billion mark and is expected to reach about five billion by 2015 (with the current world population approaching seven billion).

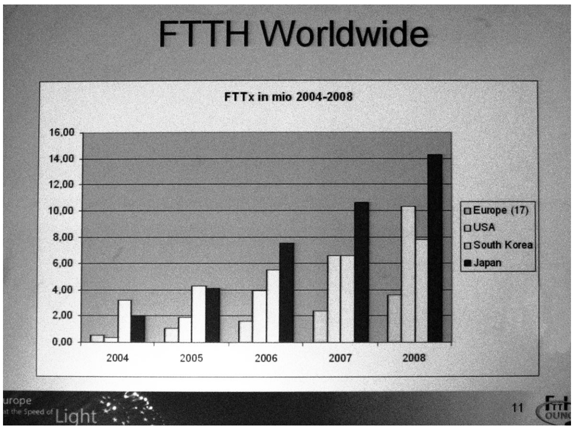

Figure 2. Number of households (in millions) connected to FTTH networks in 2004 – 2008 (Tauber H., Why a Competitive Europe Needs FTTH?, Eur. Conf. on Optical Communication, Cannes, 2006).

2.2 Fibre lasers

The first fibre laser and its potential advantages were demonstrated by Snitzer [7] as early as 1961. That was, however, before the advent of laser diodes, high-quality fibres and other fibreoptic components, including fibre Bragg gratings, which are currently utilised to build efficient fibre lasers, so Snitzer's bright idea was not developed further. However, the explosive growth of optical fibre communications since the early 1980s, with a peak at the end of the 20th century, has led to the development of all the components necessary for designing efficient fibre lasers. Advances in fibre laser technology were also contributed by the decline in the development of optical fibre communication systems at the beginning of the 21st century.

Figure 3 schematically shows a cw fibre laser. Until 2005, only fibres doped with rare earths (Nd, Yb, Er, Ho, Tm, Pr) were used as gain media in such lasers. In 2005, new gain media were proposed: bismuth-doped glass fibres [8]. The cavity mirrors in fibre lasers are fibre Bragg gratings (FBGs) inscribed into the fibre core, which require no adjustment. High-brightness, long-lived laser diodes (LDs) with fibre pigtails are used as pump sources. Thus, a fibre laser is a monolithic, compact structure, rugged and easy to operate.

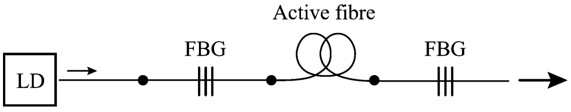

Figure 3. Figure 3. Schematic of a cw fibre laser.

Note the high (above 30%) wall-plug efficiency of Yb fibre lasers. Their pump efficiency reaches 70 % – 80 %, and the use of single-mode active fibres ensures high beam quality. The small dimensions and weight of fibre lasers are essential for a number of applications. For example, the volume of a 20-kW cw fibre laser is twice that of a modest refrigerator (Fig. 4).

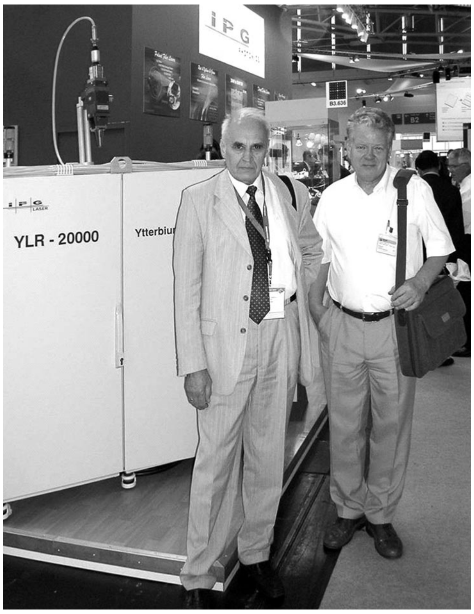

Figure 4. IPG's YLR-20000 20-kW fibre laser.

Owing to these advantages, fibre lasers have seen rapid development in recent years. The world market for fibre lasers was US $240 million in 2007 and is expected to double by 2011. Especially great advances have been made in the technology of high-power cw Yb fibre lasers, which are widely used in materials processing (welding, cutting, drilling). At a given power, fibre lasers offer higher quality and faster processing rates in comparison with high-power CO_2 lasers, which are traditionally used for these purposes. The leader in the technology of high-power fibre lasers is IPG Photonics [9]. Figure 5 illustrates the growth dynamics of the output power of cw fibre lasers.

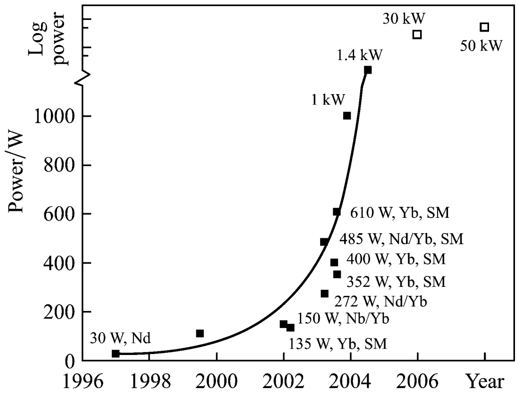

Figure 5. Growth of the maximum output power of cw fibre lasers in the past decade; SM = single-mode operation.

In recent years, there has been intense interest in femtosecond fibre lasers, which are more compact, efficient and less expensive than their bulk counterparts (e.g. the Ti : sapphire laser). This enables them to be widely used in medicine and in biological and physical research and makes them attractive for high-precision metrology of optical frequencies and creation of compact highly precise optical clocks. A fibre laser generating 50-fs pulses is palm-size. Micromachining of transparent and opaque materials (metals and semiconductors) requires femtosecond pulses up to 1 μJ in energy with repetition rates near 1 MHz. State-of-the-art femtosecond fibre lasers generate ~ 500-fs pulses with an energy of ~ 0.1 mJ [10].

The ability to extend the range of laser wavelengths is crucial for many potential applications of lasers in medicine, technology and various areas of research. This can be achieved either through frequency conversion with existing lasers or by creating new active media. Low-loss optical fibres with various core compositions enable efficient laser frequency conversion using Raman scattering. In particular, highly nonlinear, low-loss phosphosilicate and germanosilicate glass fibres form the basis of a family of efficient Raman fibre lasers emitting in the range 1.1 – 2.2 μm when pumped by an Yb fibre laser ($\lambda_p = 1.06$ μm) [11, 12].

Bismuth-doped glasses luminesce in a wide spectral range (1.1 – 1.6 μm), which opens the possibility of creating efficient fibre lasers emitting in this range. The first bismuth-doped fibre laser, emitting in the range 1.15 – 1.215 μm, was demonstrated in 2005 [8]. Later, laser action was achieved throughout the range 1.15 – 1.55 μm (see e.g. Refs [13 – 15]) (Fig. 6). Such lasers have considerable potential for use in next-generation optical fibre communication systems, and

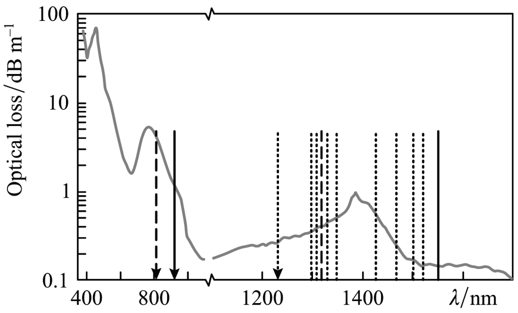

Figure 6. Lasing wavelengths obtained with bismuth-doped phosphosilicate fibres at different pump wavelengths. The grey solid curve represents the optical-loss spectrum of the fibres. The arrows indicate the pump wavelengths, and the vertical markers indicate the lasing wavelengths. The corresponding pump and lasing wavelengths are marked by the same kind of line (solid, dashed or dotted).

their frequency-doubled radiation may find application in medicine [16, 17] and astrophysics [18].

2.3 Fibre sensors

Fibre-optic temperature, pressure, strain and chemical sensors and fibreoptic gyroscopes are used in a variety of applications. The main advantages of fibre sensors are their insensitivity to electromagnetic interferences, compatibility with fibreoptic information processing and transfer systems, and small dimensions, in combination with the availability of various components [19].

In recent years, a great deal of attention has been paid to the technology of distributed fibreoptic measuring systems, primarily of temperature, pressure and strain sensors, which enable the monitoring of buildings, bridges, dams, levees, ship and aircraft hulls and other structures (Fig. 7).

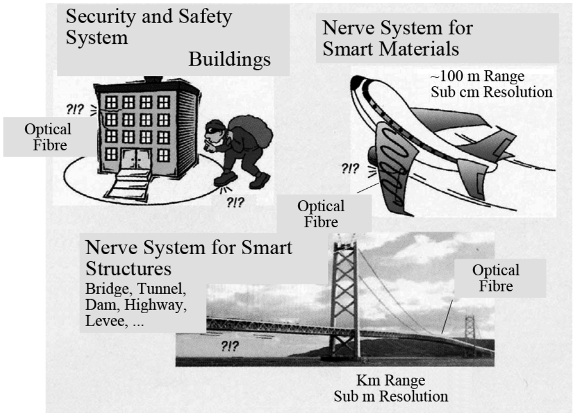

Figure 7. Fibreoptic nerve systems [Hotate K., IEEE LEOS Newsletter, **20** (1) 5 (2006)].

In the literature, such sensor systems are often referred to as fibreoptic nerve systems (by analogy with the human nerve system).

3. Prospects of fibre optics

A detailed analysis of the prospects in this rapidly growing area of science and technology, vital for modern society, is beyond the framework of this paper. Here I restrict myself to design strategies for creating the next generation of optical fibres and key fibreoptic systems (primarily, communication systems and fibre lasers). These issues are extensively discussed in the literature. The need for next-generation optical fibres is dictated primarily by modern society's demand for more advanced fibreoptic systems, which might be built only with the use of novel components.

As follows from reports and discussions at the 34th European Conference on Optical Communication (ECOC'08, Brussels, September 2008), economics, public infrastructure, education and security require the creation of next-generation optical fibre communication systems with per-fibre capacities of 50 – 100 Tbit s^{-1}. Another requirement on such systems is reduced power consumption and lower cost.

In wavelength-division multiplexed (WDM) communication systems, the total per-fibre capacity is

$$B\,(\text{bit s}^{-1}) = n\,b\,(\text{bit s}^{-1}),$$

where n is the number of WDM channels per fibre and b is the channel data bit rate.

The former goal – information transfer at a bit rate of 50 – 100 Tbit s^{-1} per fibre – can be achieved by increasing both n and b. Currently, a typical value of b is 10 Gbit s^{-1}, but commercial systems with $b = 40$ Gbit s^{-1} were demonstrated as early as 2008, and efforts have been concentrated on a system with $b = 100$ Gbit s^{-1}. According to estimates, the limiting capacity for a single 2000 km fibre is ~ 500 Tbit s^{-1} [20].

Increasing the number of WDM channels per fibre will inevitably extend the spectral range of information transmission. Currently, use is commonly made of the spectral range 1530 – 1610 nm, set by the gain bandwidth of erbium-doped fibre amplifiers. According to experts, future optical fibre communication systems will exploit the entire spectral range 1300 – 1610 nm. This in turn will require efficient fibre lasers and broadband amplifiers for the range 1300 – 1500 nm, which are currently lacking. The recently demonstrated bismuth-doped fibre lasers and amplifiers [21] would be expected to bridge the gap, but further work is still needed to enhance the efficiency of bismuth-doped fibre lasers and create broadband fibre amplifiers for this spectral region.

Another consequence of an increase in the number of channels per fibre would be a considerable rise in signal power in the single-mode fibre core, which might lead to cross-interferences because of the nonlinear interaction between optical signals. This highlights the need for next-generation light-transmitting fibres which would have either a large core (mode field) diameter (which is not easy to achieve for a single-mode fibre) or a less nonlinear core material (air?).

Consider now the latter requirement on optical fibre communication systems: reduced power consumption and cost.

It is known that Internet currently consumes more energy than global air traffic. In optical fibre communication networks, this energy is used to convert optical signals to electronic and back again [22]. The solution is obvious but not simple: all-optical signal processing. Another viable approach to reducing the energy consumption and cost is to integrate optical and electronic components on a single silicon chip. Both approaches require novel components, including highly nonlinear fibres and planar waveguides and optical components on silicon substrates (lasers, optical amplifiers, couplers, waveguides and other).

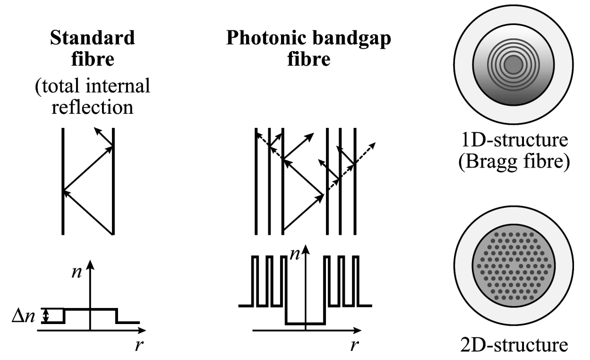

Figure 8. Mechanisms of light propagation in standard and photonic-crystal fibres.

The technology of higher power (cw and femtosecond) fibre lasers with high beam quality also requires active and passive fibres with a large core diameter in order to reduce the influence of optical nonlinearity.

Many of the challenges in designing the next generation of fibreoptic systems can be overcome by utilising photonic crystal fibres. Such fibres have a photonic crystal cladding, with a periodic transverse index profile, which leads to the formation of photonic bandgaps. In the corresponding spectral ranges, light propagation is forbidden in the cladding and is thus confined to the fibre core. Figure 8 illustrates the mechanisms of light propagation in standard fibres (total internal reflection) and photonic crystal fibres with 1D (so-called Bragg fibres) and 2D cladding structures. The refractive index of the core in photonic crystal fibres may be lower than the effective cladding index, and light can then propagate through the hollow core. Air-core fibres are of great interest because they offer the possibility of achieving lower optical losses and lower nonlinearity in comparison with the existing telecom fibres [23]. The minimum optical loss achieved to date in air-core fibres is 1.7 dB km^{-1} [24]. The optical-loss spectrum of such fibre is presented in Fig. 9. The low-loss regions correspond to the photonic bandgaps of the cladding. Further basic research is needed to elucidate the mechanisms of the optical losses in such fibres and reduce them.

Among the other advantages of photonic crystal fibres, note the much wider tunability of their key parameters, such as dispersion, nonlinearity, and mode field diameter, in comparison with conventional fibres. In particular, single-mode fibres have been fabricated with cross-sectional core areas between 700 and 1200 μm^2 ($\sim$ 100 μm^2 in standard fibres).

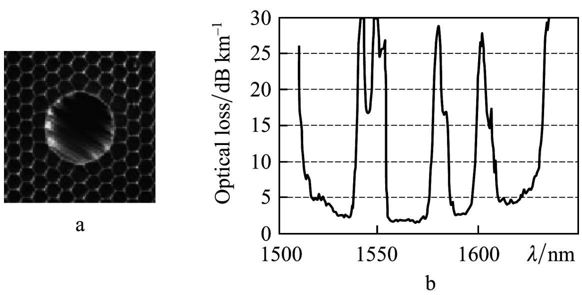

Figure 9. (a) Hollow-core fibre structure and (b) optical-loss spectrum of air-core fibres.

Photonic crystal fibre design strategies are currently the subject of intense research in many centres all over the world. Such fibres will undoubtedly find commercial application in the near future.

4. Conclusions

The ongoing rapid development of fibreoptic technologies is driven mainly by the need for higher speed optical fibre communication networks. Mankind is steadily advancing towards an information society where every person will have access to any information any time and any place.

Unfortunately, despite the high level of Russian academic science, Russia remains at the periphery of this innovative field. In other words, both the government and business sectors show little interest in supporting the development of fibreoptic technologies in our country.

The same is evidenced by the modest civilian research and development spending in Russia (percent of gross domestic product) in comparison with some other countries [25]:

1. Israel, 4.71
2. Sweden, 3.86
3. Finland, 3.51
4. Japan, 3.18
5. South Korea, 2.99
6. Switzerland, 2.93
7. USA, 2.57
8. Germany, 2.51
9. Taiwan, 2.42
10. France, 2.13
11. Australia, 1.77
12. UK, 1.73
13. China, 1.34
14. Russia, 1.07
15. South Africa, 0.87
16. Argentina, 0.46

At the same time, the country has an enormous need for large information flows in its economics, public infrastructure, education, and security. This will inevitably alter the attitude of the Government and business towards fibre optics development in Russia.

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