AN OFS **WHITE PAPER**

ADVANCED FIBERS FOR INCREASED SUSTAINABILITY AND REDUCED COSTS IN METRO/DCI APPLICATIONS

OFS FITEL, LLC

OFS, 2000 Northeast Expwy, Norcross, GA 30071

Introduction

Modern fibers should be designed to optimize the performance of the newest and most advanced transmission systems. Such systems are power hungry, but it has now proven possible for the most sophisticated optical fibers to support actual power savings of the transmission equipment. Reductions in the hunger for power could help making the internet less resource demanding – and increase the sustainability.

OFS TeraWave® ULL fiber, satisfying International Telecommunications Union (ITU) recommendation G.654.E, is one of the most prominent of such fibers, and with its low level of non-linearities and low attenuation it can help the transceiver reach an operating low-power sweet-spot. In this way the transceiver will not have to do so much "work" to clean up the received signal and this means potential power savings when compared with a standard ITU G.652.D fiber (Fig. 1).

Real-life tests done at Furukawa Electric Japan (Ref. 1) have documented that such power savings may be as high as 10W for each 600 Gbps transceiver transmitting over a 100 km span. And although 10 W does not sound like much , the total power savings for the whole 80 channel system amounted to a sizeable 14,000 kWh per year. This is equal to boiling a kettle of tea-water 140,000 times per year and even if this may sound impressive, the test system was quite small, so much larger savings may be obtained big scale.

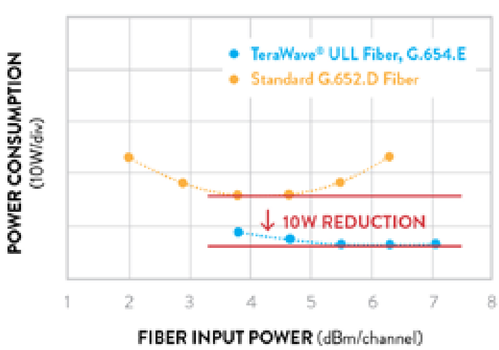

FIGURE 1: Results from real-life test of 100 km 600 Gpbs commercially available transmission system over two different fiber types. 10W reduction in transceiver power consumption per channel obtained with TeraWave® ULL fiber (Ref. 1).

Furthermore, in each situation where TeraWave® ULL fiber, allows a reduction in the number of amplifiers or regenerators, the advantage is not only in hardware cost savings opportunities – it also reduces daily power consumption since fewer amplifiers or regenerators need to be powered.

That could mean power savings every hour of the day – every year, and apart from reducing Operational Expenses, it also avoids wasting power when operating the net, which needs to be operational 24/7. That is increased sustainability.

The International Electrotechnical Commission (IEC) itself points to the 17 UN Sustainable Development Goals at their website: https://www.iec.ch/sdg and especially the goals 7, 11, 12 and 13 may probably be relevant in this context.

SOURCE: www.iec.ch/sdg

TeraWave® ULL Fiber: Benefits Especially in Metro and Data Center Interconnect Applications

Sustainability is far from being the only advantage that the TeraWave® ULL fiber has to offer.

OFS has built a network model and business case tool to analyze how G.654.E fibers can be used to save cost and power in network builds considering different traffic growth rates over 10 years. The model is based on the decisions typically facing carriers and so it assumes that a carrier deploys 12, 24, 36, 48, or 60 advanced TeraWave® ULL fibers in a composite cable (typically 144 or 288-fibers total).

The model points to significant cost saving potentials particularly at Metro distances of 800 – 1000 km.

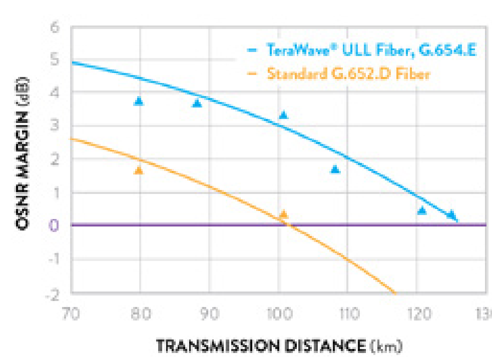

FIGURE 2: Real life transmission at 600 Gbps comparing TeraWave® ULL fiber with standard G.652.D fiber. Lines show simulation results, triangles show experimental results. 0 dB OSNR is the minimum required to obtain a Bit Error Rate of 10^{-15} (Ref. 1)

In the real world, official demos have been carried out using Ciena transmission equipment. They carried 200G over an unrepeatered link of 260 km, which was 37% further than possible over a G.652 fiber. And using 600G commercially available transmission equipment it proved possible for TeraWave ULL fiber, to transmit a 25% longer distance compared to G.652.D standard fiber without the need for amplification (Fig. 2).

More on that later.

Growing Demand for Transmission Capacity

Demand for transmission capacity just seems to be growing and growing. This is nothing new, and it is not surprising that this has brought a lot of focus to the concept of spectral efficiency.

Previously the question was often heard: "What is that maximum transmission speed over this type of fiber?" and while it was a very understandable question, the answer was always rather complex. The same type of question today would often be: "What spectral efficiency can this fiber support?"

Spectral efficiency is a measure of how much transmission capacity can be crammed into one fiber – or into certain wavelength bands of that fiber. If the same transmission capacity which needed 4 fibers yesterday may be crammed into 3 fibers today, significant cost savings may be lurking around the corner. And although fibers are typically not very costly, digging cables into the ground, splicing and installation is, and so advanced fibers may easily end up being the most cost-efficient choice in total.

Looking Back Over Our Shoulders A Bit...

If you are already now getting that familiar TLDR-feeling in anticipation of the following short hindsight of developments in transmission system techniques, you may want to just skip the next two sections and go right to the "Fibers Particularly Suited for Advanced Transmission Formats" section.

Not too many years ago optical transmission was based on the "On-Off-Keying" (OOK) transmission format. This is like using Morse code and a flashlight – pulses of light are interchanged with periods of darkness to form a code which may be interpreted by the receiver of the communication. In principle this transmission format is relatively immune to unwanted noise – because the receiver only needs to distinguish between "no light" and "full light". However, a property called Chromatic Dispersion made things pretty complex – especially at high transmission speeds. It delays some parts of the light signal relative to other parts of the same light signal – causing "blurring" on the output side of the fiber, confusing the receiver.

Then came along "Coherent transmission". Or to put it differently: coherent transmission had been used for years in RF communication (Cellular Phones, WiFi and such) but was now adopted for use in optical communication. And with Coherent Transmission came the possibility of using complex transmission formats like Quadrature Amplitude Modulation (QAM). It uses a combination of both amplitude and phase of the light signal for coding (Fig. 5). Such combinations may be illustrated with so called "constellations" (Fig. 4) and may offer extremely high spectral efficiencies. This was a quantum leap as shown in Fig. 3.

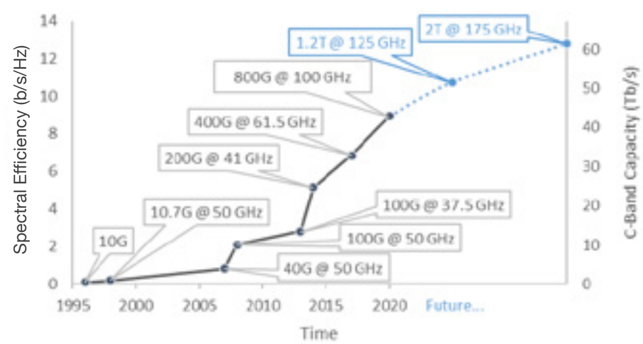

FIGURE 3: The introduction of 100G coherent transport marked a quantum leap in C-band transmission capacity. The left & right vertical axes show two different metrics for capacity per fiber. The tags on each point on the graph show the spectrum needed to carry that data rate. Over time, baud rates increase and modulation formats become more complex, requiring higher SNR in the link. [Figure courtesy of Michael Hubbard of Ciena Corp.]

These advanced transmission formats were made possible by very powerful Digital Signal Processors (DSPs). A DSP is much like the main electronic chip on the Graphics interface in a gaming-computer, where it makes millions of calculations calculating the 3D effects of high-quality moving images. But in modern transmission systems, such calculations may be used to filter and delay the signal, to cancel the effect of chromatic dispersion. This may be thought of as "calculating backwards", effectively determining what the signal looked like at the input of the fiber. And then suddenly the problems of Chromatic Dispersion have disappeared.

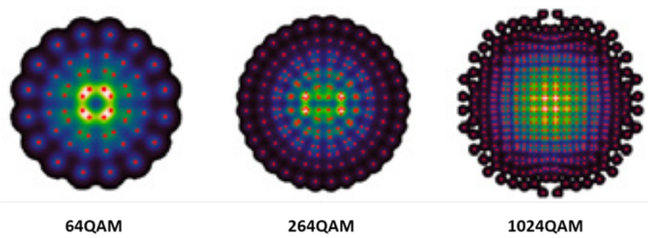

FIGURE 4: Constellation diagrams for high complexity QAM formats. The pink dots in the row and the columns represent amplitude levels and phase relationships - © 2020 IEEE. Reprinted, with permission, from Ref. 2.

Also, Polarization Mode Dispersion (PMD) can be counter-acted using the DSP.

Advanced Transmission Formats Like QAM

While dealing with Chromatic Dispersion and PMD and allowing for the use of advanced transmission formats like Quadrature Amplitude Modulation (QAM), coherent transmission techniques are able to cram a lot of transmission capacity into a fiber *(high spectral efficiency)*. As always, however, there are no free lunches.

The general rule is that the more advanced the modulation format (QAM16 → QAM32 → QAM64) the higher the spectral efficiency – but regrettably the more sensitive the transmission also becomes to noise and to non-linearities in the fiber. The non-linearities of the fiber effectively put a limit to how much optical power the fiber is able to handle. High order modulation formats attempt to divide this limited optical power into a number of closely spaced intervals. The higher order modulation format, the higher the number of intervals – which means that each interval has to be smaller – and hence more susceptible to noise (Fig. 5).

For example, in QAM16 the optical receiver must be able to distinguish not only between "full light" and "no light" but between 4 levels of light (and furthermore 4 phases). For QAM64 it is 8 levels of light (and 8 phases – a total of 64 combinations).

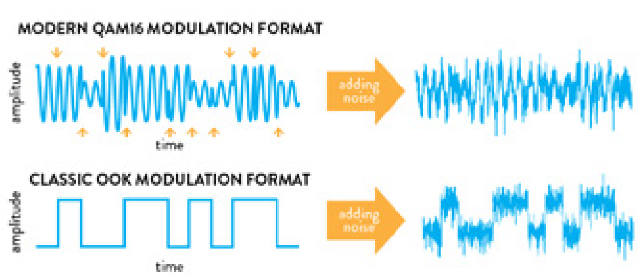

FIGURE 5: Upper left is QAM16 signal. Orange arrows point to phase shifts (sharp spike-type curve sections). Multiple amplitude levels are visible. Upper right is QAM16 signal with noise. Difficult if not impossible to detect phase shifts and amplitude levels.

Lower left is classic OOK signal.
Even after adding same level of noise, the signal is legible.

Noise is unavoidable in transmission systems, and Fig. 5 illustrates that the previously used OOK transmission format is less sensitive to noise than a modern QAM16 format.

Fibers Particularly Suited for Advanced Transmission Formats

Keeping noise (almost) out of the signal can be accomplished by reducing amplifier spacing or by using more advanced amplifier types. Both these solutions, however, may be costly and energy consuming – not the least if additional amplification huts need to be built to house the amplifiers. Furthermore, amplifiers add noise to the signal themselves.

Another option is to use a fiber like the TeraWave® ULL fiber, featuring a very low attenuation. Sometimes both of these solutions need to be used – but a low attenuation fiber will always lend a helping hand to advanced transmission formats enabling higher spectral efficiencies.

A perhaps less obvious complication is the unavoidable non-linearity of a glass fiber. If low power light is injected into an optical fiber, the fiber will behave linearly. When the optical power is increased, however, one or more non-linear effects will start to affect and distort the transmitted light signal. Such distorted signals are difficult for the receiver to interpret correctly and the number of transmission errors will increase. This requires more frequent re-transmission, stealing transmission capacity.

In general, more advanced modulation formats are more sensitive to non-linearities. Some findings indicate that to obtain error free transmission using high-constellation modulation formats, a low non-linearity of the fiber can be even more important than a low attenuation. And this may appear already on transmission distances as short as 100 – 200 km for 600 Gbps transmission

In fibers with large cores the light is spread out over a larger area and can consequently carry light of higher power before non-linearity problems set in. TeraWave® ULL fibers offer large effective areas of 125 μm^2 – which are considerably larger than the typical effective areas of 82 μm^2 of standard G.652.D fibers. This advantage can be used to allow highly complex transmission systems to operate over the fiber, expanding the transmission capacity of the fiber.

The Short Story of the ITU-T G.654 Recommendation

The G.654 recommendation was born in 1988 and intended for submarine transmission (Fig. 6). In an optical fiber it is normally possible to obtain a much lower attenuation around 1550 nm (the C-band) than around 1310 nm (the O-band) and, since low attenuation was already then essential, G.654 fibers were intended for transmission around 1550 nm. To enable the use of large cores the cutoff wavelength was allowed to be as high as 1530 nm. For such fibers, the chromatic dispersion is relatively high and that was for many years an important limiting factor in long distance transmission.

ITU-T Recommendation G.654		
	Nominal MFD @ 1550 nm	Max. Macrobending Loss @ 1625 nm
G.654.A	9.5 - 10.5 μm	0.50 dB
G.654.B	9.5 - 13.0 μm	0.50 dB
G.654.C	9.5 - 10.5 μm	0.50 dB
G.654.D	11.5 - 15.0 μm	2.0 dB
G.654.E	11.5 - 12.5 μm	0.1 dB

FIGURE 6: ITU-T G.654 recommendations. A and C specify rather small Effective Area fibers (roughly similar to G.652.D standard fibers). B and E specify medium-to-large Effective Area Fibers with E requiring the same tolerance to bending as standard terrestrial fibers. D covers very large Effective Area fibers which are allowed to be quite sensitive to bending.

Macrobending loss is for 100 turns at 30 mm radius.

With coherent transmission systems, the advantages of the G.654 fibers again became significant. Focus today is on the low attenuation C-band around 1550 nm. In case other transmission bands are needed to increase the capacity of the fiber, the L-band (wavelengths longer than 1565 nm) is the most likely candidate because the attenuation in that band is almost as low as in the C-band.

With large cores, however, fibers become more sensitive to bending, handling and installation – and hence the TeraWave® ULL fiber has been designed to meet and exceed the most recent G.654 recommendation – G.654.E – which was made to help good bending performance even for fibers with an effective area as large as 125 square microns. This is particularly true for terrestrial applications, the target of both TeraWave® ULL fiber and G.654.E, where fiber handling is much different from submarine applications, target of the bulk of the G.654 recommendation.

OFS Fibers Complying with G.654			
	Nominal Effective Area (1550 nm)	Complies with G.654	Attenuation (1550 nm)
TeraWave® Fiber	125 μm²	B, D, E	Max. 0.19 dB/km
TeraWave® ULL Fiber	125 μm²	B, D, E	Max. 0.17 dB/km
TeraWave® SCUBA125 Fiber	125 μm²	B, D	Nom. 0.156 dB/km
TeraWave® SCUBA150 Fiber	153 μm²	B, D	Nom. 0.155 dB/km

FIGURE 7: OFS offer a number of large core transmission fibers in the G.654.B, G.654.D and G.654.E categories.

The large effective area of TeraWave® ULL fiber enables high optical power to be used in each transmission channel. This can enable either the use of more complex modulation formats, hence allowing more capacity on a single fiber, or longer transmission spans without amplification, hence saving the cost of amplifiers.

In combination with this, the attenuation of TeraWave® ULL fiber, is significantly lower than what is required in the most modern G.654 recommendation (G.654.E). OFS offers a sister-fiber called TeraWave® SCUBA125 fiber with the same effective area, but with an even lower attenuation. This fiber is typically intended for submarine applications (Fig. 7).

TeraWave® ULL Fiber Comes with a "Goodie Bag" of Advantages and Opportunities

Using a coherent transmission system, you may "swap" a somewhat longer amplifier spacing for a somewhat shorter total transmission distance - and vice versa. This increases the flexibility.

Also, the complexity of the modulation format results in both pros and cons. Typically, for example, QAM16 may transmit over longer distances than QAM64 – but QAM64 is able to cram more capacity into the fiber. A slightly different way to view this is shown in Fig. 8, which is based on Fig. 1 in Ref. 2. The most important properties of the cited "hero experiments" are recreated in Fig. 8 showing this general trend – for example: 40 km reach of a 178 Tbps transmission compared with around 10,000 km reach of a 50 Tbps transmission.

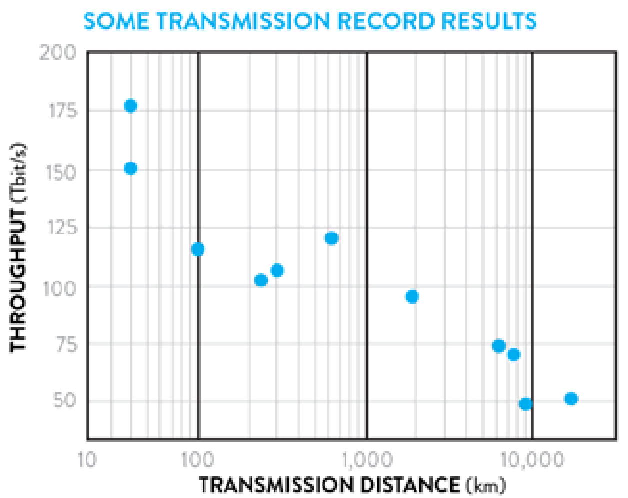

FIGURE 8: Based on results from "hero-experiments," this figure illustrates the tendency that shorter transmission distances correlate with higher transmission throughput of a fiber optic link. TeraWave® ULL fiber helps increase transmission distance or throughput – or some of each – compared to standard G.652.D fibers. Adapted from style of Fig. 1 in Ref. 2, © 2020 IEEE. Used with permission.

To push back the barriers of these limitations, more advanced (and often more costly) amplifiers like RAMAN and Hybrid Raman EDFA (HRE) amplifiers may be deployed. Another standard technique used is Forward Error Correction (FEC) which "steals" a bit of transmission capacity and adds some latency to the transmission, but which in return increases transmission distance. Early FEC techniques were used already on classic 40 Gbit OOK systems.

But the actual choice of transmission fiber is also very important. The advantages offered by the combination of the very low attenuation and the large effective area of the TeraWave® ULL fiber may be thought of as a "goodie bag" of opportunities. These opportunities may be freely utilized to improve the transmission exactly where it is needed the most, in one or more of the following ways:

- Increasing the amplifier spacing thereby possibly reducing the number of required amplifiers and perhaps also the number of (new) amplifier huts, power supplies, cooling etc.
- Sometimes amplifiers can even be avoided altogether. In a real-life test TeraWave® ULL fiber, was able to transmit 600 Gbps 25% longer than standard G.652.D without amplification (Ref. 1).
- Increasing the maximum overall transmission distance without requiring regenerators.
- Increasing the capacity of the fiber by using highly advanced transmission formats with higher spectral efficiency. Fewer fibers may need to be lit and may alternatively be used for future expansions getting the full benefit of the sunk costs of deploying cables, huts and amplifiers.
- Increasing the capacity of the fiber by additionally using the L-band from 1565 nm to 1625 nm rather than just the standard C-band from 1535 nm to 1565 nm. Long wavelength transmission is sometimes problematic because fiber bending loss increases with longer wavelengths, but TeraWave® ULL fiber offers excellent bending performance even at L-band wavelengths.
- Network futureproofing: Development of new, more advanced, and more demanding transmission systems happens quickly. Not too long ago 600G was introduced, and now 800G is just entering the scene. Even if the current network requirements may be fulfilled by standard G.652.D fibers, TeraWave® ULL fibers still offer more headroom to support future upgrades of transmission gear.

Cost Savings Enabled by TeraWave® ULL Fiber

TeraWave® ULL fibers are more costly than standard G.652.D fibers and so the potential cost savings offered by TeraWave® ULL fibers have to be larger to obtain overall cost savings.

Such a cost calculation will depend on a lot of different choices – type of transmission system, amplifier types, amplifier spacing, total distance - but also growth rate of needed transmission capacity and number of fibers in the cable.

As mentioned, OFS has built a network model and business case tool to analyze how G.654.E TeraWave® ULL fiber can be used to help save cost and power in network builds.

In one case, the model calculates the number of TeraWave® ULL fibers that has to be deployed, to help minimize total costs by reducing the number of amplifiers and line cards otherwise needed for standard G.652 fibers. The higher initial cost of the G.654.E fibers is compensated by lighting up such fibers more slowly, which is possible because they have higher spectral efficiency and support greater capacity per fiber.

In another case, the model assumes a required unregenerated distance and a required data rate and calculates the potential saving due to avoiding costly regeneration.

The model points to significant cost saving potentials particularly at Metro and DCI distances at 800 – 1000 km and in some analyses TeraWave® ULL fiber, savings of up to 25 – 35% relative to standard G.652.D fibers have been found.

And the Extra Treat in the Goodie Bag: Added Sustainability.

As briefly mentioned, daily power savings would normally be considered to increase sustainability.

With the low level of non-linearities and low attenuation the TeraWave® ULL fiber can help the transceiver reach an operating sweet-spot. In this way the DSP of the transceiver will not have to do so much "work" to clean up the received signal and this means power saving opportunities when compared with a standard G.652.D fiber.

But the fiber may also allow using a smaller number of amplifiers and regenerators (both needing power) as well as potentially allowing the use of less advanced amplifiers with a lower power consumption.

Real-life tests (Ref. 1) have documented that such power savings may be as high as 10W for a 600 Gbps transceiver – and power savings could also result from a reduction of the number of transponders needed since fewer fibers need to be lit when the added capacity of TeraWave® ULL fiber is utilized.

So, the total power savings may be substantial.

Summary

TeraWave® ULL fiber offers the possibility for transmission equipment power savings – and hence improved sustainability. This may be obtained, not only by potential reductions in the number of amplifiers and transceivers, but also by helping the transceivers reach an operating sweet-spot in which the power consumption of the transceiver itself is reduced.

Advanced fibers offer the potential for minimizing Operational as well as Capital Expenditures, and having now been deployed on 3 continents, TeraWave® ULL fibers have already verified the good theoretical results in real world situations. We expect advanced fiber will continue offering advantages to support further development of transmission systems using complex modulation formats.

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